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Research Article

Benefits and Risks of Truck Platooning on Freeway Operations Near Entrance Ramp

Meng Wang[1], Sander van Maarseveen[1], Riender Happee[2], Onno Tool[3], and Bart van Arem[1]

Abstract

Truck platooning attracts considerable attention thanks to the promising fuel consumption benefits and business model. Nevertheless, concerns over the influence of long truck platoons on other traffic are raised by road operators. It is intriguing to understand under what conditions truck platooning will influence other traffic and what are the magnitudes of the influence. To this end, this paper reports a simulation study on examining the effects of truck platooning on freeway operations near an on-ramp. Systematic experiments were conducted with varying demand, market penetration rates (MPRs), intra-platooning gap, and platoon size. Moreover, three alternative strategies for truck platooning to accommodate merging traffic were tested: allowing courtesy lane change of trucks, active yielding, and keeping a larger intra-platoon gap than the acceptable gap for human drivers to change lane. Simulation results show that at high MPRs of truck platooning, the system mitigates congestion and increases throughput, at the expense of merging failures. The merge location distributions shift toward the end of the acceleration lane at congested flow and high MPRs. The effect on average merging speed is insignificant, but the merging speed in saturated traffic with truck platooning shows larger variability. At free flow and low MPRs, the influence is insignificant. Evaluation of the three alternatives concludes that the yielding strategy is most effective in resolving the merging problem with truck platooning. Courtesy lane change is not always possible because of the high speed difference between lanes and keeping a larger time gap suppresses the benefits in congestion mitigation and throughput increase.

Connected automated vehicles (CAVs) possess potential in improving traffic operations. Vehicle platooning is a highway CAV application characterized by a string of CAVs keeping short spacing and with the clear benefit of increased roadway capacity (*1–3*). As a subclass of the vehicle platooning problem, truck platooning has received much attention because of the pronounced benefits of fuel saving and promising business models (*4*).

Several truck platooning field tests have been conducted in Europe under the SARTRE project (*5*), the COMPANION project (*6*), the Grand Cooperative Driving Challenge (GCDC) (*7*), and the European Truck Platooning Challenge (*8*), demonstrating the technical feasibility and the benefits of fuel saving. In the U.S.A., PATH started research into automated vehicle platoons more than two decades ago (*9*) and performed field tests with truck platoons recently (*10–12*). The Japanese Energy ITS project also demonstrated the benefits of truck platooning in energy savings (*13*). While acknowledging the potential benefits of truck platooning for the trucks, concerns have been raised over difficulties that large platoons may bring to other vehicles, especially at freeway entrance/exit sections (*4*, *8*, *14–16*). Such sections are often freeway bottlenecks, that have paramount implications for the safe and efficient operations of a freeway. From a road operators' perspective, truck platooning systems not only shall have technical and safety benefits for the truck fleet, but guarantee safe and efficient traffic operations at the collective level as well. However, questions about the impacts of truck platooning on freeway operations and in what conditions it can bring benefits, or even risks, remain largely unanswered in the literature.

This paper aims to gain insights into the influence of truck platooning on freeway operations during transitional periods with mixed traffic conditions. A vehicle-

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following model for truck platooning with collision-avoidance functionality is built in an open-source microscopic traffic simulator. The lane change model in the simulator captures the synchronization and relaxation behavior near merges and the behavioral adaptation of accepting smaller gaps in the presence of truck platoons. Systematic simulation experiments are designed and conducted to identify the potential benefits and problems of truck platooning in mixed traffic with varying demand, market penetration rates (MPRs), intra-platooning gap, and platoon size. Moreover, three alternative strategies for truck platooning that may tackle the potential problems at merges are tested: allowing courtesy lane change of trucks, active yielding, and keeping a larger intra-platoon gap than the acceptable gap for human drivers to change lane. Merging location distribution, merging speed distribution, frequency of merging failure, network outflow and total time spent in the network were chosen as indicators to assess freeway operations at both microscopic and macroscopic levels. Assessment gives insights into the presence and magnitude of the influence of truck platooning on traffic and provides recommendations to circumvent the identified problems.

To get valid freeway operations in simulation, a longitudinal behavior model for cooperative truck platoons should be developed and the interaction between truck platoons and other traffic should be considered. To this end, there will first be a review of relevant literature in these two categories, which lay the foundation for the platoon behavior model development and choices in the sequel.

Relevant Work on Cooperative Adaptive Cruise Controllers and Car-Following Models

Although truck platooning may involve lateral vehicle control, the majority of truck platooning systems being tested to date only controls the longitudinal motion and the lateral motion is under human driver control. Therefore, this review focuses on the longitudinal behavior for automated platoons. The longitudinal control system for vehicle platooning is often referred to as a Cooperative Adaptive Cruise Control (CACC) system. The indispensable building block of the CACC controller is the ACC controller, which aims to track the leader/predecessor with some desired distance (17–22). The most widely used ACC controller is a linear controller, in which the desired acceleration is proportional to the gap error and speed error with respect to the preceding vehicle in vehicle-following mode, with the aim of follow-the-predecessor with a constant time gap (CTG). This linear controller has been extensively studied (23–25). Non-linear state-feedback ACC controllers with

variable time gap policies have been reported for better string stability performance (26, 27) or being able to operate in full range with collisions avoidance functionality (28, 29). Predictive controllers for platooning systems have also been proposed to generate optimal behavior under a performance index and handle constraints explicitly (30). But there is no evidence that the variants of these nonlinear controllers is being used in production vehicles.

Distributed CACCs extend the ACC controller by including the acceleration of the predecessor (17, 18, 31, 32). The fundamental mechanism that distributed CACC systems exhibit much stronger string stability performance is because of the fact that the predecessor acceleration serves as the feedforward term in the control system, thus the controlled vehicle can better anticipate and react to the disturbance. CACC variants with communication of multiple predecessors (32) or of both platoon leader and direct predecessor have been reported. The information from beyond the line of sight of on-board sensors provides anticipation of future dynamics and thus is favorable for stability. String stability of the CACC controller is often a design requirement (32) and the corresponding car-following model of CACC should represent this behavior (33, 34).

Car-following models have been used to model ACC/CACC systems in microscopic simulation. Notably, the Helly-type car-following model (35) has been used extensively (19, 33, 34, 36, 37), since it bears great resemblance to the linear CTG controller in relation to mathematical formulation and the equilibrium gap-speed relation. With the same problem as the linear CTG controller, the Helly-type model cannot guarantee there will be no collisions, which is an essential feature for microscopic traffic simulation. Therefore, system deactivation and control authority transition between ACC/CACC systems and human drivers have to be modeled explicitly to avoid collisions (34).

The Intelligent Driver Model (IDM) and the Optimal Velocity Model (OVM) have been used to design ACC/CACC controllers to resemble human car-following behavior (26, 38–41). The issue with IDM and OVM-like models is that the equilibrium gap is a nonlinear function of speed, thus pertaining to a variable time gap policy rather than the CTG policy employed by standard ACC/CACC systems. In addition, one confusion that often appears in the literature is that the safe time gap parameter in IDM is different from the desired time gap for standard ACC/CACC systems. At equilibrium conditions, the time gap between vehicles governed by IDM is larger than the safe time gap parameter of the model because of the nonlinearity of the model. (One can easily verify this by setting the acceleration and relative speed of the IDM to zero and deriving the equilibrium gap-

speed relation.) Care should be taken when comparing the desired time gap of standard ACC systems with the safe time gap parameter of IDM. Note also that most of the car-following models for ACC/CACC are not validated and calibrated against empirical data. To the best of the authors' knowledge, the only car-following model that is based on empirical ACC/CACC behaviors is reported by PATH (*33*) and is later extended to full speed range with system deactivation (*34*).

To summarize, several CACC controllers or models for truck platooning have been proposed, which aim to track the predecessor with CTG and guaranteed string stability. To operate in full speed range, they often have to be integrated with a warning system, based on which the drivers can intervene at safety-critical conditions, or with an automated collision avoidance system.

With regard to the interaction of automated truck platoons with human drivers, it is expected that behavioral changes will occur for merging vehicles. However, the collective impact of truck platooning on traffic flow performance and safety is not investigated in a systematic manner. Relations between truck platoon size, truck platooning gap, and adaptive strategy at merging sections are not reported either. These reveal the scientific gaps to be filled by this paper.

In the remainder, we first present how the truck platoon behavior is modeled, followed by the simulation experiment design. The simulation results are then discussed, with insights into the microscopic and macroscopic traffic impacts of truck platooning.

Truck Platooning Model in Traffic Simulation

Truck Platooning Operational Assumptions

It is assumed that cooperative trucks are able to control the longitudinal motion at the full speed range and safety-critical conditions and they will remain in automation mode on freeways. Platoon formation takes place in the network in an ad-hoc way ("on-the-fly") (*31*). Equipped trucks only initiate platoon formation if their qualified predecessor (e.g., an equipped truck) is within the communication range, for example, 200 m, and the platoon size is below its maximum. The platoon follower catches up with their equipped predecessor by increasing its desired speed from 85 km/h to 90 km/h. CTG policy is used to resemble plausible driving behavior of ACC/CACC systems from original equipment manufacturers (OEMs) (*31*).

Longitudinal Model Formulation

To represent the truck platoon behavior, the closed-loop behavior of automated truck platoons should maintain a constant time gap at equilibrium conditions, attenuate disturbance along the platoon, and avoid rear-end collisions with predecessors. These are the main requirements for the proposed model. The following second-order vehicle dynamics model for longitudinal motion of trucks are adopted:

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} x_i \\ \dot{x}_i \end{pmatrix} = \begin{pmatrix} \dot{x}_i \\ u_i \end{pmatrix} \tag{1}$$

where x_i and v_i denotes the position and speed of vehicle i, and u_i denotes the control input, or desired acceleration, of the ACC/CACC vehicle. Assuming the lower-level actuators track the acceleration perfectly, the desired acceleration is the same as the realized acceleration.

The proposed ACC/CACC controller is an extension of the full range ACC controller in Mullakkal-Babu et al. (*29*):

$$u^{\mathrm{f}} = k_s(s_i - s_{d,i}(v_i)) + k_{\Delta v}R(s_i)(v_{i-1} - v_i) + k_a a_{i-1} \tag{2}$$

where u^{f} denotes the desired acceleration in the following mode. $s_i = x_{i-1} - x_i - l_i$ is the gap/spacing between vehicle i and its predecessor $i-1$, with l_i denoting the vehicle length. $s_{d,i}$ is the desired gap of the vehicle i, following the CTG policy with

$$s_{d,i} = v_i t_d + s_0 \tag{3}$$

where t_d is the desired time gap and s_0 is the net gap at standstill conditions. $k_s, k_{\Delta v}, k_a$ are constant gains for the gap error, speed error, and the feedforward predecessor acceleration, respectively. $R(s)$ is a nonlinear term in the control law, which is a decreasing function of gap:

$$R(s) = 1 - \frac{1}{1 + Qe^{-s_i/P}} \tag{4}$$

where Q is called the aggressiveness coefficient. Q determines the strength of braking response at small gaps. P is the response range, within which the response increases exponentially. The term governs the behavior in such a way that when vehicle i approaches the predecessor at small gaps, the second term of the control generates sufficient deceleration to avoid driving too close to the predecessor (*29*).

When the predecessor is a non-equipped vehicle, the CACC controller of vehicle i degrades to an ACC system by removing the feedforward term in Equation 2:

$$u^{\mathrm{f}} = k_s(s_i - s_{d,i}(v_i)) + k_{\Delta v}R(s_i)(v_{i-1} - v_i) \tag{5}$$

t_d for ACC system is 1.5 s, much larger than the CACC platooning time gap in the range of 0.3–0.7 s.

In addition to the vehicle-following mode, there will be a cruising mode in real traffic where there is no predecessor or if the predecessor is out of the sensor range.

The control objective is to maintain a predefined cruising speed v^c :

$$u^c = k_c(v^c - v_i) \tag{6}$$

The final acceleration signal is achieved by:

$$u_i = \min\{u^f, u^c\} \tag{7}$$

The controller parameter values were tuned based on tracking performance, string stability, and collision-free properties. k_s is tuned from previous work (29). The parameters of $k_{\Delta v}$, P and Q should be tuned according to desired time gap so as not to introduce overshoot and oscillation while keeping the string stability property at small gaps. They are tuned based on the nonlinear function of $R(s)$ (4) and the simulated response of the controller in typical driving scenarios (29, 42). The details of the tuning process and results can be found in Section 3.4 and Appendix E in van Maarseveen (42).

The final parameters used are: $Q = 20$, $P = 40$, $k_{\Delta v} = $ 3.52 s^{-1}, 2.10 s^{-1}, and 1.93 s^{-1}, when $t_d = $ 0.3 s, 0.5 s, and 0.7 s, respectively. $k_s = $ 0.3 s^{-2}, $k_c = $ 0.18 s^{-2}, and $s_0 = $ 3 m.

Model Performance Verification in Typical Driving Scenarios

The performance of the (C)ACC controller is loosely verified via simulating the behavior of a single truck platoon with three trucks in several single-lane typical driving scenarios. The scenarios are defined to represent freeway traffic situations, including: normal driving with small disturbance, stop-and-go, emergency braking, cut-in, cut-out, approaching and longer platoon scenarios (29, 34). Figure 1 shows the resulting trajectories of truck platoons under three challenging scenarios, while the systematic verification results can be found in van Maarseveen (42). Verification showed that the controller is able to generate safe driving behavior in critical conditions and gives a smooth acceleration response. Disturbances of the acceleration responses are attenuated with this controller.

Human Driver Model and Merging Behavior Adaptation

Realistic merging behavior generated by the lane change model of the traffic simulation is crucial for the validity of the simulation results. Important behaviors in the vicinity of merging sections, including anticipation, accepting smaller gaps than equilibrium, cooperation, and relaxation, should be captured in the integrated lane change and car-following model (43–45). After a comprehensive review of existing lane change models (42), we chose the lane change model with relaxation and

synchronization (LMRS) and the improved Intelligent Driver Model (IDM+) as the core behavioral components of the traffic simulation (46). The lane change model in the simulator captures the synchronization and relaxation behavior near merges and the simulation model has been calibrated for Dutch and U.S. freeways (46, 47). The human car-following model, IDM+ , is an improved version of the original IDM model (48) and has been shown to reproduce more realistic capacity values and shock wave speeds (46). Truck platooning is implemented by replacing the acceleration model of IDM+ with the truck acceleration model described in the previous section.

To capture the macroscopic flow characteristics of truck platooning in automated vehicle systems, the interactions between conventional vehicles and automated truck platoons should be modeled properly. Although large-scale field tests were not available, some busy freeways with a considerable percentage of trucks where they are already driving like a "platoon" can shed some light on the interactions of platoons with other traffic. A platoon of conventional trucks on the outermost lane of freeways can occur when there is substantial freight traffic, which leads to behavioral changes of merging vehicles (49). Notably, the most important behavioral adaptation is the acceptance of smaller gaps when merging in the presence of conventional truck platoons. This behavioral adaptation is implemented in MOTUS to make the merging behavior more realistic. When evaluating a lane change decision, a lane change by human drivers is therefore now executed when the resulting gap with the putative equipped truck follower is no less than 0.3 s (normally around 0.5 s). This minimum gap is only accepted if the merging vehicle's lane change desire is the strongest, that is, it is near the end of the acceleration lane.

Experimental Design

Simulated Network

The road network simulated represents the A67 between Eindhoven and Venlo in the Netherlands. This freeway represents one of the busiest freight routes in the Netherlands and among others is a very important connection from the port of Rotterdam and Antwerp to the hinterland. Based on A67 operational characteristics, the following model choices/assumptions are made:

- The simulated network represents a two-lane freeway section with an on-ramp.
- The speed limit matches that of the A67 Eindhoven–Venlo: 130 km/h.
- The length of the acceleration lane is 350 m according to the Dutch design standards.
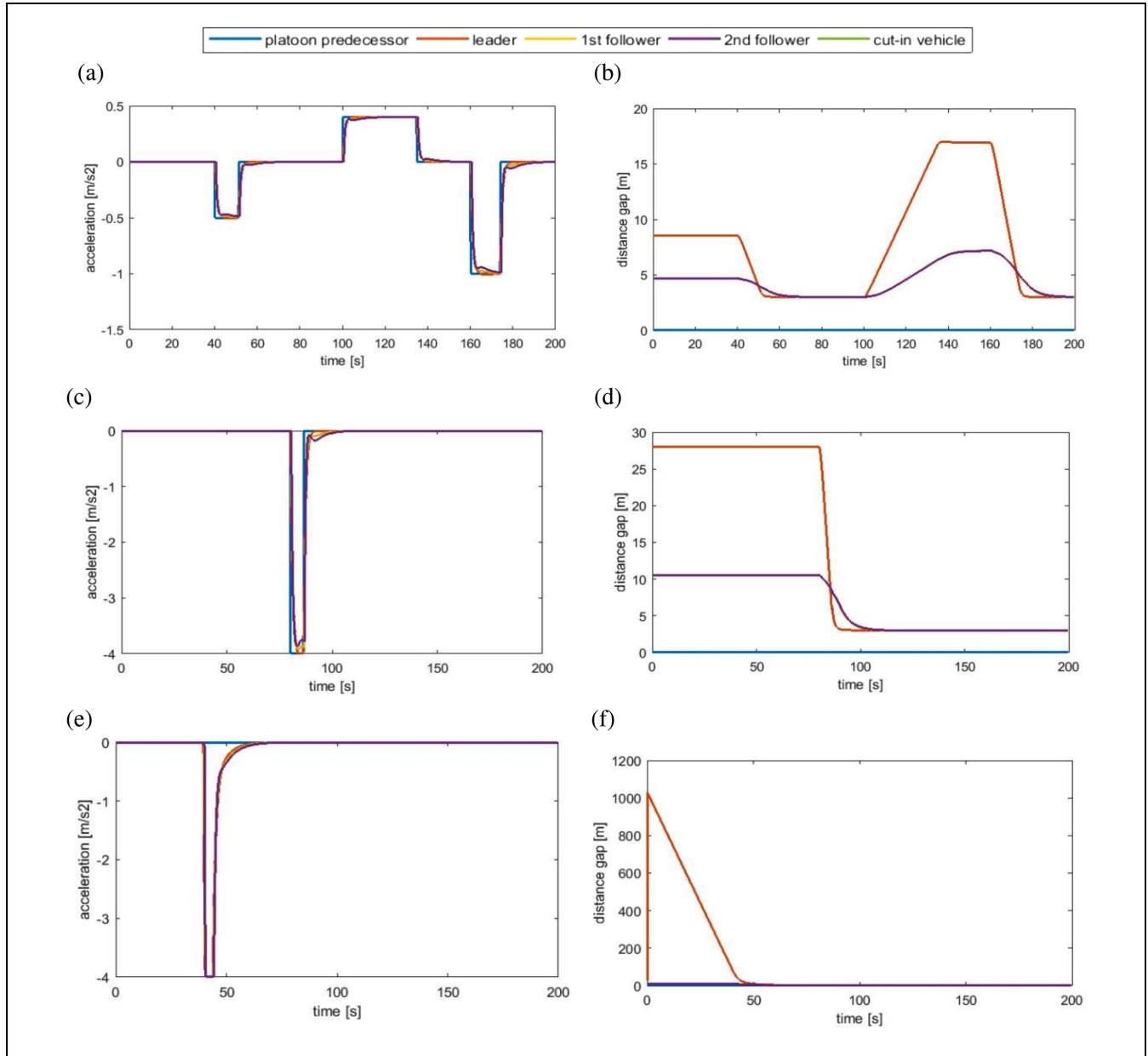
Figure 1. Performance verification of the CACC controller in typical driving scenarios: (*a*) platoon acceleration under stop-and-go scenario, (*b*) platoon speed under stop-and-go scenario, (*c*) platoon acceleration under emergency braking scenario, (*d*) distance gap under emergency braking scenario, (*e*) platoon acceleration under approaching scenario, and (*f*) distance gap under approaching scenario.

- Drivers on the freeway and on the on-ramp can already see each other approximately 100 m before the start of the acceleration lane to allow for anticipation.

The simulated road network has a total length of 6,350 m. There is a 4,000 m warm-up stretch followed by a 350 m section beginning at the start of the acceleration lane. Virtual loop detectors are placed on the freeway every 200 m, as shown in Figure 2. On the acceleration lane itself, loop detectors are placed every

50 m to allow for more precise analysis of merging behavior. On the first 50 m of on-ramp, the speed limit is 50 km/h so that the acceleration behavior on the acceleration lane is realistic. A warm-up period of 5 min is used to fill vehicles in the simulation network.

Truck Platoon Configuration and Experiment Variables

The experimental variables are mainly related to the platooning configuration and are listed below:
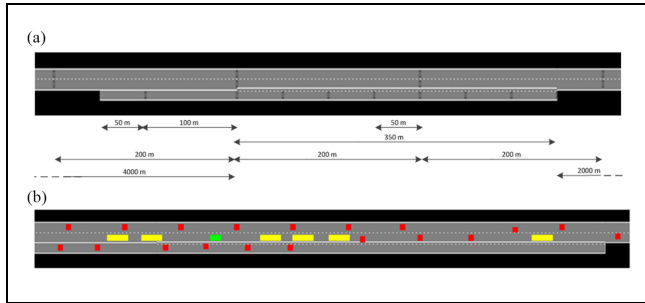
Figure 2. (*a*) Aerial view of the on-ramp area of the road network with detector locations and dimensions, and (*b*) detailed view of traffic at the acceleration lane with truck platoons.

- Maximum platoon size: (1) Two trucks; (2) Three trucks.
- Fixed intra-platoon/CACC gaps: (1) 0.3 s; (2) 0.5 s; (3) 0.7 s.
- Traffic intensity: (1) low; (2) medium; (3) high; (4) congestion.
- Equipped truck MPR: (1) 0% (base scenario); (2) 25%; (3) 50%; (4) 75%; (5) 100%.
- Alternative platooning strategies to accommodate merging: (1) allow yielding; (2) allow lane changing; (3) keep a larger time gap of 0.9 s (> minimum acceptable gap).

The intensity and demand are derived from empirical data from National Data Warehouse and are detailed in Table 1.

The platooning strategy of *allow yielding* and *allow lane change* and the time gap of 0.9 s are only simulated with congestion intensity. This design results in a total number of 388 scenarios. The relevant scenarios are run with 20 replications per scenario. Each simulation run represents 1 h of traffic. A simulation time step of 0.2 s is used.

Assessment Indicators

A set of indicators to assess the influence is used.

Merge Location Distribution. This is a histogram indicating the frequency of occurrence of merge locations and its standard deviation. It gives an indication of how well merging vehicles are able to merge. Late merging or even inability to merge might lead to dangerous situations. If a vehicle is (almost) unable to merge, it is shown in the bar chart by the bar representing the end of the acceleration lane.

Merging Speed Distribution. This indicator demonstrates the average merging speed observed on the acceleration lane. The speed samples are instantaneous speeds at the time when the merging vehicles start to change lane to the mainstream line. They are grouped into spatial grids of 50 m along the acceleration. The indicator gives an indication of how well vehicles are able to synchronize their speed to the vehicles on the freeway and thereby the severity of disturbances in the traffic flow caused by the on-ramp.

Total Time Spent in the Network. The total time spent (TTS) is calculated from the vehicles' trajectories in the simulation by taking the sum of the time spent in the network by each individual vehicle over all vehicles generated during simulation. It gives an indication of network performance expressed in time. It is advantageous over a delay indicator since it does not require defining a base case without delay, which is subject to uncertainty.

Maximum Outflow (QoutMax). Maximum outflow is calculated by repeatedly calculating the average outflow during an aggregation period of 5 min using a moving average method that moves 1 min per calculation and

Table 1. Demand and Truck Share Setting

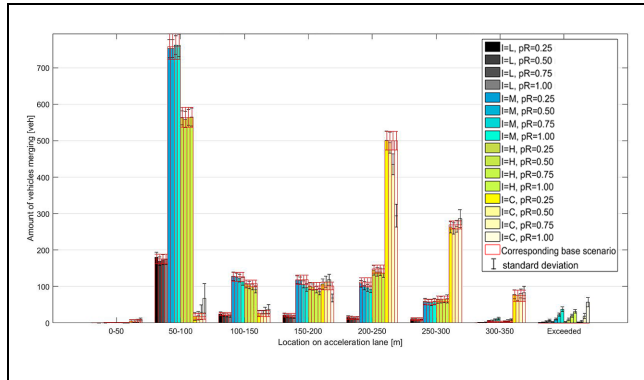|		Free flow			Congestion
Intensity		Low	Medium	High	Saturated
Time of day		Early morning	Afternoon	Morning peak	–
Motorway	Total [veh/h]	660	1,178	2,426	4,000
	Share of light trucks [%]	10.9	10.1	5.2	5.0
	Light trucks [veh/h]	72	119	126	200
	Share of heavy trucks [%]	45.3	29.7	14.5	20.0
	Heavy trucks [veh/h]	299	350	352	800
On-ramp	Total [veh/h]	240	1,171	982	1,000
	Share of light trucks [%]	5.8	5.2	6.3	5.0
	Light trucks [veh/h]	14	61	62	50
	Share of heavy trucks [%]	30.8	2.0	2.5	2.0
	Heavy trucks [veh/h]	74	23	25	20

Figure 3. Merging location distribution.
Note: I = intensity; L = low (free flow); M = medium (free flow); H = high (free flow); C = congestion; pR = penetration rate.

then taking the maximum calculated value. The aggregation period of 5 min prevents a bias in the result. Flow data from the most downstream detector is used.

Speed and flow contour plots are also used to identify the congested states and patterns.

Insights into the Influence on Traffic Performance

In this section, we discuss the influence of truck platooning at microscopic and macroscopic levels. The reference scenario produced by the simulation model has been validated based on the capacity value, shock wave speed, and spatiotemporal congestion dynamics. The validation shows the model is capable of generating the congestion pattern, plausible capacity value of 2,056 veh/h/lane on Dutch freeways, and shock wave speed of 20 km/h. The simulation model also captures the capacity drop phenomenon. For details of the validation, readers are referred to van Maarseveen (*42*).

Merging Location Distributions

The merge location distributions of the platooning scenarios, aggregated for the different platoon configurations, are displayed in Figure 3. The merge location distributions hardly change in all three free flow scenarios. Most vehicles merge within 50 to 100 m after the

start of the acceleration lane. Almost all vehicles have merged after 300 m. In the congestion scenarios, however, most vehicles merge between 200 and 250 m after the start of the acceleration lane. Also, many vehicles still need to merge at between 300 and 350 m. Compared with the base scenarios, the average merge location is shifted a few meters more toward the end of the acceleration lane.

The most significant differences with the base scenarios occur at the end of the acceleration lane. As more truck platoons are present, more vehicles merge in the last 50 m of the acceleration lane. In congestion, a slightly larger share of vehicles is merging earlier than in the base scenarios, especially at higher penetration rates. Figure 3 also reveals that some vehicles are unable to merge within the length of the acceleration lane. This indicates that merging becomes more difficult in the presence of truck platoons. This problem grows with increasing penetration rate and traffic intensity.

The average number of vehicles per hour that are unable to merge within the length of the acceleration lane is given in Table 2 for the different traffic intensities and penetration rates and aggregated for the different platoon configurations. It reveals that serious merging problems will occur only at higher penetration rates, even for a medium traffic intensity. For a penetration rate of 25% or lower, hardly any vehicles are unable to merge in time. The fact that inability to merge occurs more often for medium traffic intensity than for high traffic intensity reveals that the intensity on the on-ramp is more determining for merging issues than the intensity on the freeway itself.

Merging Failures in Relation to Platoon Configurations

The effects of truck platooning on merging behavior is different for the maximum platoon sizes and the CACC time gaps considered. A maximum platoon size of three trucks increases merging problems compared with a maximum platoon size of two trucks as illustrated in Figure 4*a*. This is because a platoon of three trucks is longer than a platoon of two trucks and therefore forms a longer barrier for merging vehicles. The number of vehicles unable to merge in time increases with higher on-ramp traffic intensities and penetration rates. The

Table 2. Average Number and Share of Vehicles Unable to Merge Per Hour

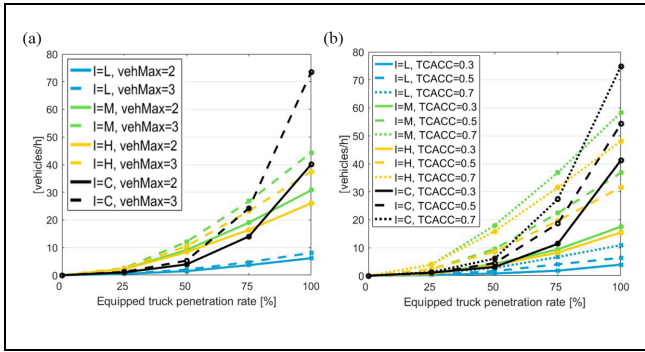|	MPRs				
Traffic intensity	0%	25%	50%	75%	100%
Low	0	0.5 (0.2%)	1.8 (0.75%)	4.1 (1.7%)	7.1 (3.0%)
Medium	0	2.4 (0.2%)	10.6 (0.9%)	22.9 (2.0%)	37.5 (3.2%)
High	0	2.3 (0.2%)	9.4 (1.0%)	19.8 (2.0%)	31.8 (3.2%)
Congestion	0	1.1 (0.1%)	4.6 (0.5%)	19.1 (1.9%)	56.8 (5.7%)

Figure 4. Merging failure analysis based on platoon configuration: (*a*) merging failures per platoon size and (*b*) merging failures per time gap.

Note: TCACC = time gap of CACC; vehMax = platoon size limit.

number of vehicles unable to merge in time can be almost 1.5 times as high as in free flow and twice as high as in congestion for a maximum platoon size of three trucks at high intensities and penetration rates. The rest of the merge location distribution is hardly different for the two maximum platoon sizes.

Smaller CACC time gaps reduce the number of vehicles unable to merge in time as shown in Figure 4. This is because a platoon with a larger time gap (yet still smaller than a human acceptable gap) is longer than a similar platoon with a smaller time gap and therefore forms a longer barrier for merging vehicles. The decrease in the number of vehicles unable to merge in time is larger for higher traffic intensities and penetration rates. Thereby the effect is largest for medium and high traffic intensities. The number of vehicles unable to merge in time can be more than three times as high as in free flow and almost twice as high as in congestion for a CACC time gap of 0.7 s compared with a

CACC time gap of 0.3 s at high penetration rates. Similar to the two maximum platoon sizes, the rest of the merge location distribution is hardly different for the three CACC time gaps.

Note that although the average number and share of vehicles unable to merge per hour in the medium traffic intensity scenarios in Table 2 are similar to (or even higher than) high intensity scenarios, this may be caused by the random effects of the simulation.

Merging Speed Distributions

The distributions of speeds at which vehicles merge hardly change because of truck platooning as shown in Figure 5 for the different traffic intensities and penetration rates. Similar to the base scenarios, they increase along the acceleration lane from approximately 75 up to 100 km/h during free flow. The congestion scenarios do not show large differences with the base scenario either. However, in congestion, the merging speeds show a large variability with truck platooning as reflected by the high standard deviations when compared with the base scenario.

The penetration rate only has a significant effect on the merging speeds when it is higher than 50% as shown in Figure 5. As illustrated earlier, the number of vehicles unable to merge in time increases with increasing penetration rate. Since these vehicles are deleted from the simulations, they are not included in the calculation of the average merging speeds. In reality these vehicles would still have to merge by either stopping at the end of the acceleration lane and waiting for a suitable gap or by continuing on the shoulder lane. Therefore, the increase in average merging speeds as observed in the simulations is likely to be smaller in reality.
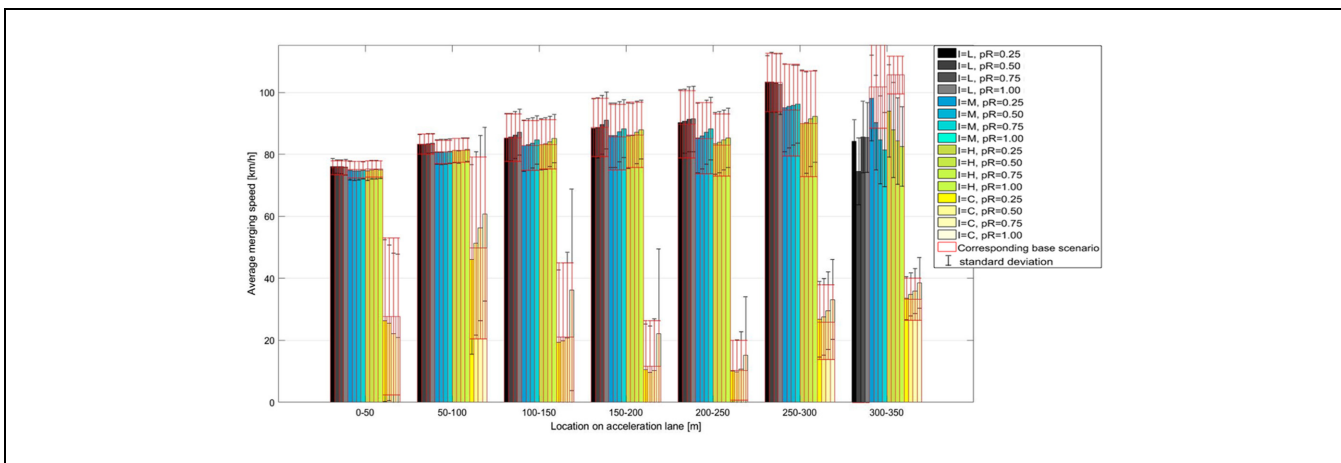

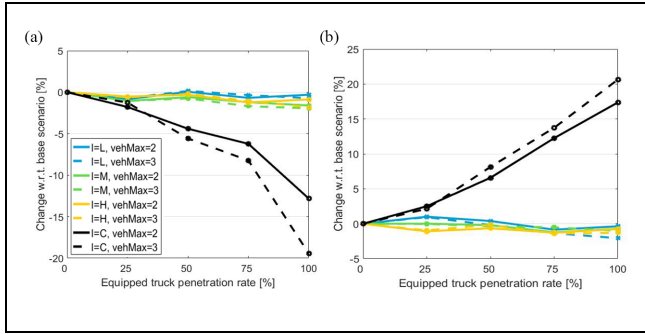**Figure 5.** Merging speed distribution.

Figure 6. Relative changes with respect to (w.r.t.) the base scenario for different platoon sizes: (*a*) total time spent and (*b*) maximum outflow.

Macroscopic Changes with Fixed Time Gap

In free flow, the effects of truck platooning on the TTS are small, as shown in Figures 6*a* and 7*a*. During congestion, the decrease in TTS is much larger. It decreases with increasing penetration rate up to approximately 16% on average when all trucks are equipped. Again, the reduction in TTS thanks to truck platooning is likely to be over-estimated because of deleted vehicles with failed merging.

The maximum outflow confirms the pattern found for the TTS, as shown in Figures 6*b* and 7*b*. During free flow the effect of truck platooning on maximum outflow is negligible, but during congestion a significant effect on maximum outflow (equivalent to capacity) prevails. It is found that maximum outflow increases linearly with increasing penetration rate. At 25% penetration rate the capacity increase is limited to approximately 2% on average, but it increases by up to 19% (to 4,563 vehicles/h) when all trucks are equipped as shown in Figure 7*b*. This is a major capacity increase, illustrating one of the

positive potential effects of truck platooning on traffic flow. Once again, apart from the contribution of truck platooning, the increase may be (partially) caused by the fact that some vehicles are deleted and do not merge, so that the traffic flow on the freeway is disrupted less than if these vehicles would have merged.

Analysis of the flow- and speed-contour plots reveals that no significant differences in traffic states occur because of truck platooning in free flow. In congestion the differences with the base scenario are much larger as shown in the speed contour plot in Figure 8. The congestion becomes less severe because of truck platooning, since the traffic speed after traffic breaks down is higher with truck platooning at 100% MPRs compared with the base scenario. In congestion and at high penetration rates, truck platooning also has the effect of delaying the jam formation as shown in the speed-contour plots in Figure 8. This can be attributed to the stabilizing effects of truck platooning with string-stable CACC systems, which leads to better resilience of the traffic flow against merging disturbance.

Possible Solutions to the Truck Platooning Problem

In this section, the effects of the three alternative truck platooning strategies to actively accommodate merging traffic are further discussed.

Platooning with Yielding

One intuitive solution is to allow the equipped trucks to open larger gaps to yield for the merging vehicle, which is one of the active platooning strategies (*15*). The simulation with this strategy reveals that allowing truck platoons to
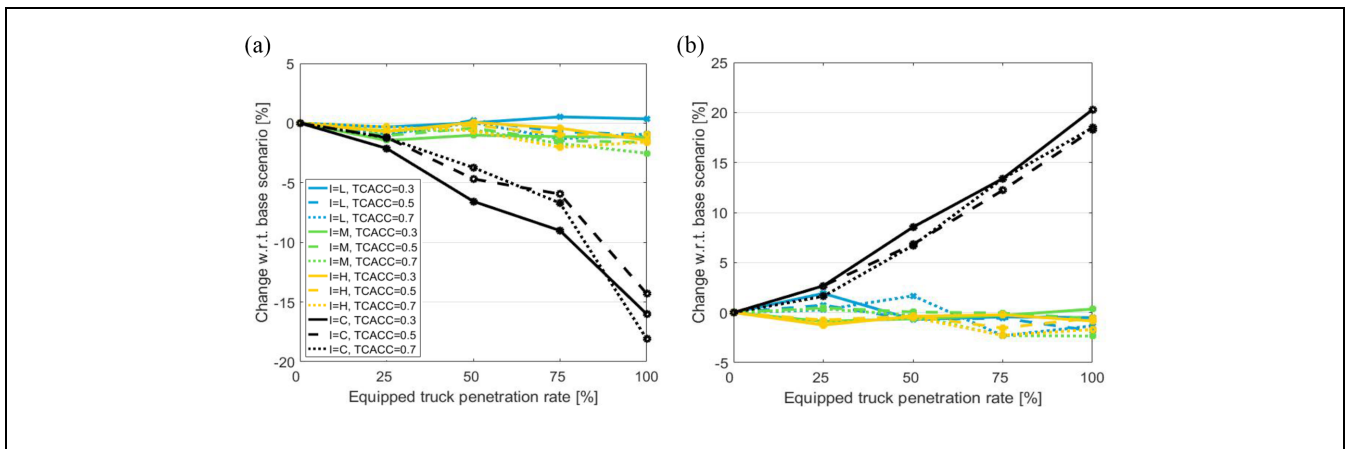

Figure 7. Relative changes with respect to (w.r.t.) the base scenario for different time gap settings: (*a*) total time spent and (*b*) maximum outflow.
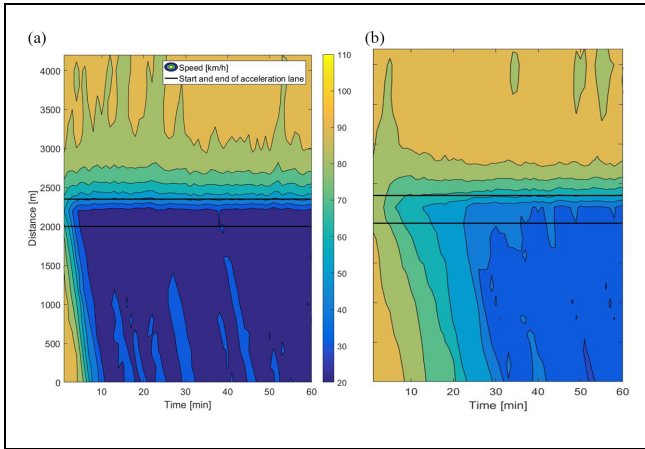
Figure 8. Speed dynamics of (*a*) the base scenario and (*b*) 100% truck platooning.
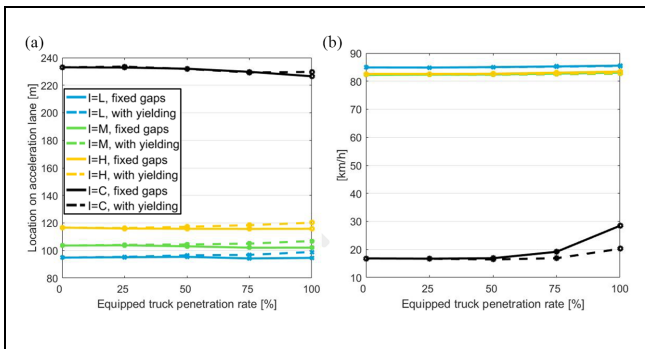

Figure 9. Comparison of merging location and merging speed with and without the yielding strategy: (*a*) comparison on merging location and (*b*) comparison on merging speed.

yield for merging vehicles effectively solves merging problems. Merging vehicles are no longer unable to merge in time. Instead, those vehicles now merge within the last 100 m of the acceleration lane. This is reflected in the average merge location: it shifts a few meters further toward the end of the acceleration lane as shown in Figure 9*a*. Apart from the latter, the merge location distribution bears much resemblance to the "fixed gaps" strategy.

The fact that all vehicles can now merge has the result that the average merging speed in congestion increases much less with increasing penetration rate than with the fixed gaps strategy as shown in Figure 9*b*. The average merging speed is now only different from the base scenarios (0% MPR) if more than 75% of the trucks are equipped and increases with only 3 km/h on average when all trucks are equipped. Interestingly, allowing yielding also has the effect that the differences in merge location and merging speed distributions between the maximum platoon sizes and the CACC time gaps are reduced and become almost zero.
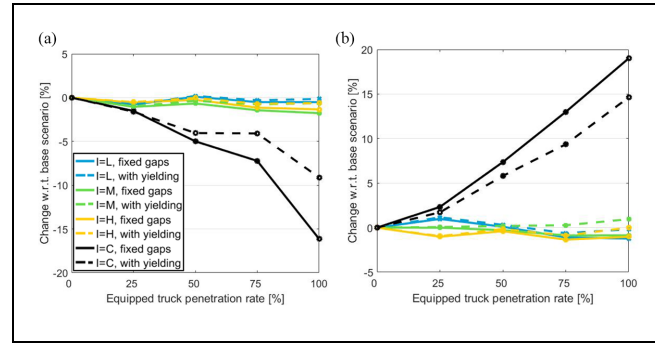

Figure 10. Comparison of TTS and maximum outflow with and without the yielding strategy: (*a*) comparison on TTS and (*b*) comparison on maximum outflow.

If platoons are allowed to yield for other vehicles, the benefits of truck platooning on traffic flow become smaller than with the fixed gaps strategy. The total time spent in the network by all vehicles is still reduced compared with the base scenarios, but less than with the fixed gaps strategy as shown in Figure 10. The maximum TTS reduction in congestion is now 9% (was 16%) and the maximum increase in maximum outflow 15% (was 19%), corresponding to 4,395 vehicles/h. This shows that even when no vehicles are deleted because of merging failures, there is still a potential capacity increase when truck platooning reaches high MPRs.

Although allowing yielding has no effect on the differences between the maximum platoon sizes, the differences between the CACC time gaps increase a little. The TTS can now be up to approximately 5% (was 3%) smaller and the maximum outflow up to approximately 4% (was 2%) higher for the smallest CACC time gap of 0.3 s compared with the largest gap of 0.7 s. This can be caused by the fact that a truck platoon driving at small CACC gaps takes longer to create a suitable gap for merging vehicles when yielding than a platoon with larger gaps.

The flow- and speed-contour plots only differ from the fixed gaps strategy in the case of congestion. The onset of congestion is faster and the breakdown of traffic is more severe, thereby shifting more toward the base scenario as shown in Figure 11. This is caused by the fact that, similar to the base scenarios, all vehicles are now able to merge and all vehicles, including the truck platoons, are able to yield for merging vehicles. Allowing yielding thus has the effect that the impact of truck platooning on traffic flow becomes smaller than with the fixed gaps strategy. However, the onset of congestion is still later and the speeds in the jam are still higher than in the base scenario as can be seen when comparing Figure 11*b* with 8*a*. This difference is larger with increasing penetration rate, reasserting the benefits of truck platooning with CACC systems in increasing capacity and stabilizing traffic flow (*31*).
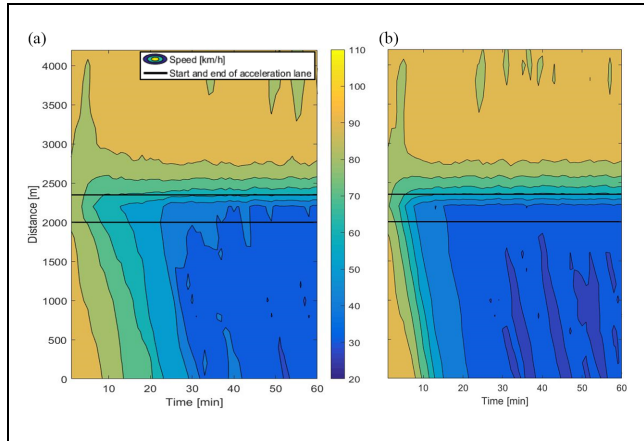
Figure 11. Comparison of speed dynamics in congestion with and without the yielding strategy: (*a*) 100% MPR with fixed gaps and (*b*) 100% MPR with yielding.

Allow Lane Change

The second solution to the merging problem with the presence of truck platoons is to allow a courtesy lane change of equipped trucks to the left to create a gap for merging vehicles. If platoons are allowed to perform such lane changes, the results do not change in free flow compared with when it is not allowed. This is because in practice hardly any trucks actually change lanes to the left because it is either simply too crowded in the left lane or the speed difference with the left lane is too high. Merge locations and merging speeds as well as the number of vehicles unable to merge in free flow are therefore not different from those described earlier for the fixed gaps strategy.

In congestion, however, there is a significant difference compared with the case in which the platoons are not allowed to change lanes. The number of vehicles unable to merge is significantly decreased by up to approximately 50% when all trucks are equipped. This results in a very slight reduction of the TTS, but the maximum outflow is not affected. Neither the flow nor the speed contour plots reveal differences with the scenarios in which platoons could not change lanes.

CACC Time Gap Larger than the Acceptable Gap to Change Lane

The third solution is to regulate the time setting of truck platooning such that the intra-platoon gap is larger than the minimum gap that is accepted by human drivers. This allows on-ramp vehicles to merge between two trucks in a platoon without active yielding. Merging vehicles, having the full lane change desire at the end of the acceleration lane will then accept merging within a truck platoon just before the acceleration lane is exceeded. This

was simulated for a CACC gap of 0.9 s. It has the effect that more vehicles are able to merge successfully in free flow. The reduction of the number of vehicles unable to merge in case of a CACC time gap of 0.9 s compared with 0.7 s is approximately 35–60% in free flow. The effect is only slightly larger with an increasing penetration rate. During congestion, an effect on the merging behavior is not observed. Similar to the "allow yielding" strategy, the CACC time gap of 0.9 s reduces the effects of truck platooning on the TTS and the maximum outflow.

Findings and Recommendations

Main Findings

Systematic simulation showed that truck platooning hardly affects traffic flow in relation to TTS and maximum outflow in free flow conditions. The congestion scenarios, however, reveal a potential road capacity increase of 2% up to 19% on average. This is caused by higher flows with truck platooning in the right lane. With high MPRs of truck platooning, the congestion also becomes less severe with higher speed in congestion and the onset of congestion is postponed compared with the base scenario. This reveals the benefits of CACC systems employed by truck platooning in increasing roadway capacity and string/flow stability.

From the results with fixed time gaps, it is found that truck platooning makes merging more difficult. More vehicles merge in the last 50 m of the acceleration lane and many may be unable to merge in time. This problem gets worse as there are more truck platoons in traffic. Apart from the number of truck platoons, the on-ramp traffic intensity is the major determinant for the severity of merging problems. Although vehicles that are not able to merge in time are simply deleted in the simulations, in reality they will still need to merge, which they could either do from standstill with a very high collision risk or by driving on the shoulder lane, causing other safety issues. This may lead to increased disruptions in the traffic flow, lessening the initial outflow benefit implied by truck platooning. In free flow, the average merge location and merging speed are mostly independent of the platoon configurations. They depend almost entirely on the traffic intensity.

Larger platoon sizes increase merging problems considerably, also at lower traffic intensities and penetration rates. However, at the same time, the capacity in the case of a maximum platoon size of three trucks instead of two trucks can increase by up to 8%, but the increase is only significant for penetration rates above 25%. As long as CACC time gaps applied by truck platoons are smaller than the minimum acceptable gap for merging vehicles, the number of vehicles unable to merge in time will considerably increase with an increasing CACC time

gap. This effect is largest for high and medium traffic intensities. A CACC time gap of 0.3 s results in an extra capacity increase of 1–2% maximum compared with 0.7 s when all trucks are equipped.

If platoon members are allowed to yield a gap for merging vehicles, the merging problems are solved completely. Regardless of the traffic intensity and penetration rate, all vehicles are then able to merge in time. It is also found that when allowing truck platoons to yield for merging vehicles, the positive effects of truck platooning on traffic flow performance still hold, even though the effects are smaller because more vehicles are merging.

Allowing platoon members to change lanes only solves merging problems partly, reducing merging failures by up to 50% at high penetration rates. This happens especially in congestion because trucks are then better able to change lanes because of even speeds across lanes. In free flow the speed difference with the left lane is simply too large for the truck platoons to be able to change lanes safely.

The third alternative of regulating the truck platoons with a CACC time gap larger than the minimum gap accepted by merging vehicles can also reduce merging problems, but only in free flow. However, this strategy reduces the flow benefits and induces more cut-in lane changes, thereby disengaging the platoon.

Summarizing, truck platooning at freeway on-ramps causes merging problems that are more widespread as there are more truck platoons, as the platoons are longer and as the traffic intensity on the on-ramp increases. This problem can be effectively solved by allowing platoon members to yield a gap for merging vehicles. Allowing platoon members to perform courtesy lane changes or having the platoons drive at larger inter-vehicle gaps also reduces merging problems, but does not resolve it completely. Truck platooning can potentially increase road capacity, but the increase is only significant at high penetration rates. At high MPRs, the severity of congestion can be reduced and the onset of congestion delayed.

Recommendations for Road Operators

The study shows that the introduction of truck platoons on the freeway will lead to merging problems at on-ramps, but the problems are marginal at low traffic intensities. This means a time frame could be implemented, for example, allowing truck platooning at on-ramps only during off-peak time. At higher traffic intensities, especially at high on-ramp intensities, truck platooning at on-ramps is not recommended. Even when few equipped trucks are present, there will be vehicles that cannot find an acceptable gap. A policy on whether truck platooning at freeway on-ramps is allowed could be based on the requirement that the number of vehicles unable to merge

should not increase compared with the current situation without automated truck platoons.

A role for the infrastructure emerges in providing information beyond the line of sight of the on-board sensors to drivers of trucks in a platoon. In that way automated vehicles can be made aware of potential merging issues when approaching an on-ramp from far upstream, so that truck platoons can already increase their inter-vehicle gaps.

Although a platoon of three trucks causes significantly more merging problems than a platoon of two trucks, a platoon of two trucks still causes them as well, which is why truck platooning at on-ramps should be discouraged for higher traffic intensities, regardless of platoon size. It is recommended to limit the maximum platoon size allowed on the freeway based on the size that is considered acceptable by road users.

Small platoon inter-vehicle gaps are desirable to prevent most cut-in lane changes, but these small gaps also proved to cause merging problems. It is therefore recommended to allow truck platooning at time gaps as low as 0.3 s if technically feasible and reliable, but to prohibit it at on-ramps at higher traffic intensities or require an active yielding strategy.

An exception to a prohibition of truck platooning at on-ramps could be made if truck drivers are required by law to create a gap for merging vehicles when necessary. However, such a strategy could well prove itself ineffective since human drivers may take a long time to take back control after automated driving. Platooning systems incorporating collision warning and collision avoidance functions are the solution along this line. This problem may be solved if truck OEMs are required to incorporate an automated platoon disengagement system that recognizes forced merging. This also means that truck platooning on freeway sections with many on-ramps in close proximity would become rather unattractive given the many formations and disengagements required at small time intervals, as shown by Yang et al. (*12*).

Recommendations for Future Research

The fact that vehicles are deleted in the simulation model when unable to merge in time can be a large limitation to the prediction validity of the flow benefits of truck platooning. In reality these vehicles will still need to merge, causing more disruptions in the traffic flow. This effect should be properly modeled in traffic simulation, which presents a challenge for future research.

In the coming years, a truck platoon facilitation strategy could be developed by road authorities. This could include a study of suitable time frames in which truck platooning at on-ramps is allowed. A method to have this information available in equipped trucks should then be

researched, so that equipped trucks know when they have to disengage, since relying on the human driver may be very unreliable. This could involve installing roadside units that communicate with equipped vehicles. One could take this even further by tuning the arrival times of truck platoons and merging vehicles, so that a merging vehicle will never arrive at the acceleration lane at the same time as a truck platoon. This would allow truck platooning at on-ramps even at higher intensities. Research could be done on the urgency of installing such a system at particular on-ramps and the associated costs. To achieve this, cooperation with truck OEMs should be considered to harmonize the workings of the required technologies.

Other measures that prevent merging issues altogether rather than solving them may also be researched. Changes to the road design is one option. An extension of acceleration lanes could for instance be considered. However, given the limited acceleration capability of vehicles, this may still lead to merging problems if the arrival times of the merging vehicle(s) and the truck platoon are conflicting. Another possibility is to introduce a dedicated lane for automated vehicles or even for truck platoons only, or prohibiting truck platoons to drive in the right lane while allowing them to drive in the adjacent lane to the left. Such research should include cost–benefit analyses to quantify the costs and compare these with the gains.

Author Contributions

The authors confirm contributing to the paper as follows: study conception and design: MW, SvM, RH, OT, BvA; controller development: MW, SvM; simulation: SvM; analysis and interpretation of results: SvM, MW; draft manuscript preparation: MW, SvM. All authors reviewed the results and approved the final version of the manuscript.

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