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Impacts of large-scale truck platooning on Dutch highways

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Abstract

Autonomous driving has a potential to improve the future road transportation. Truck platooning is one of the main solutions. However, the impact of truck platooning on traffic flow and safety on highways is still unclear. This research focuses on impacts of large-scale truck platooning on Dutch highway. It applied a microscopic modeling to simulate the impact of truck platooning within critical traffic locations such as merging and diverging areas. The results showed that large-scale truck platooning has an impact on the traffic safety and efficiency within these traffic locations compared to the current situation.

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Keywords: Truck platooning; Microscopic simulation; Traffic safety, Traffic efficiency

1. Introduction

Urban road traffic will increase in the upcoming years due to urbanization. In the Netherlands, there has been an increase of 20% on mobility in the last 10 years (Rijksoverheid, 2008). With the increase of mobility, traffic conflicts can become more common and the overall traffic safety can decrease (Peeta et al., 2005). In 2015, traffic conflicts increased with 9% compared to the year 2014 (CBS, 2017). The prediction is that by 2020 the mobility in the transport sector will increase from 15% to 80% (Rijksoverheid, 2008). Since freight transportation has an extensive road usage, this increase may lead to many negative side effects such as moving bottlenecks and an increase in greenhouse gas emission (Janssen, et al., 2016). Therefore, it is urgent to find a sustainable urban mobility development that could improve quality of life and reduce greenhouse gas emissions (Garau, et al., 2016).

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Truck platooning is one solution that can possibly resolve these problems. A platoon can be described as a cooperative system with individual trucks as sub-systems (Bergenhem, et al., 2012). For a platoon of trucks to function, a longitudinal controller is implemented. This controller makes use of a range sensor such as radar or lidar and more importantly, communication between vehicles. This communication contains the desired acceleration of the preceding vehicle, which makes it possible for the platoon of vehicles to drive closely together, achieving following gaps of up to 0.3s (Janssen, et al., 2016). Given this short inter-vehicle distance, a platoon of trucks can be considered as a single large vehicle. However, new matters arise with the implementation of the truck platoon. First, the motivation of the potential of heavy vehicle automation concepts is largely economic, promised increasing productivity, decreased fuel consumption and minimizes losses due to avoidable crashes (Nowakowski, et al., 2015). Fuel consumption depends on the distance between trucks and the speed of a platoon (Larsson, et al., 2015). Thus, platooning is profitable under specific conditions. It is unclear how these profits would perform in current and future traffic situations. Moreover, excessive traffic can reduce the efficiency of truck platooning (Larsson, et al., 2015). Second, the safety issue is unclear for the truck platoon, especially at merging and diverging sections of freeways. According to literature, sideswipe collisions have the highest likelihood of occurrence in these sections (Golob, et al., 2004; Laval and Daganzo, 2006).

To solve these problems, this research explores the impacts of large-scale truck platooning on traffic flow, efficiency and safety at merging and diverging sections of a Dutch highways A15 using a microscopic simulation model. The rest of the paper is organized as follows. First, real traffic data is collected and described in section 2. Moreover, a data analysis has been conducted to provide a realistic simulation foundation. In section 3, a microscopic simulation model is built using VISSIM. The simulation results are discussed in details in section 4. The paper ends with a conclusion and discussion.

2. **Data and descriptive analysis**

The Netherlands has high traffic intensity due to high population density and high intensity of freight traffic. 78% of the total traffic on the Dutch road infrastructure is cars and 6% is freight transportation. To set up a realistic foundation for the simulation, traffic data from detector loops of the A15 corridor of the Netherlands is collected. The A15 is the main ITS (Intelligent transport system) corridor from the port area to inland endpoints. 80% of the trucks stay within a radius of 50 kilometers from the port of Rotterdam and eventually, the trucks will ride up to Venlo. The A15 is partially a six-lane highway and heavily used by trucks. Every minute, there are 12 trucks registered at the A15 Botlecktunnel (Janssen, et al., 2016).

The traffic data from the A15 is obtained from the knowledge institution of the Port of Rotterdam. The data is captured detected by detector loops in the road infrastructure. The dataset contains the data of the velocity and intensity of various vehicles of the left and right carriageway of the A15 corridor. The data is collected by the detector loops of the left carriageway from measurement post 1.103 up to 216.620 and of the right carriageway from measurement post 26.084 up to 216.587. The descriptive analysis is executed for both vehicle categories (cars and trucks) using data of the measurement post 47.635 of the left carriageway near the Port area. The dataset of this measurement post had the least invalid data and lies near the port area of Rotterdam. The dataset contains the data from the period 1st of January until the 31st of December of the year 2015 (365 days). In the period of September until December 2015 the data is not registered correctly and therefore 11 days out of 100 days is used in the analysis. The velocity and intensity of the traffic are registered per minute from 00:00 until 23:59. Table 1 presents the mean and standard deviation of the velocity and intensity of Cars and Trucks. It can be seen that the velocity of the A15 near the port area is lower than the maximum speed that is allowed (100 km/h). The intensity shows that per hour there is on average 1414 cars and 232 trucks. The standard deviation for intensity is relatively high which means that there is quite some difference among different hours and days of the year.

Table 1. Mean velocity and intensity of cars and trucks

	Mean Velocity [Km/h]	Std. Dev. Velocity	Mean Intensity [Veh/h]	Std. Dev. Intensity
Cars	93,39	16,573	1414,46	1110,92
Trucks	79,28	13,248	231,99	269,247

Table 2. Mean velocity and intensity of cars and trucks during the peak hours and off-peak hour within different seasons

	Mean velocity cars [km/h]	St. Dev	Mean intensity cars [Veh/h]	St. Dev	Mean velocity trucks [Km/h]	St. Dev	Mean intensity trucks [Veh/h]	St. Dev
Winter peak hour (06:30 – 09:30)	83.50	17.68	3337.67	1017.62	74.81	13.91	440.77	176.13
Winter peak hour (15:30 – 19:00)	71.80	24.60	3465.32	931.05	64.42	20.00	413.98	195.66
Winter off-peak hour (09:31 – 15:29)	92.96	8.28	2168.50	692.15	82.22	6.37	631.46	219.82
Remaining seasons Peak hour (06:30 – 09:30)	81.86	19.45	2458.18	1151.84	73.71	15.67	462.34	181.67
Remaining season Peak hour (15:30 – 19:00)	71.81	23.26	2497.87	981.94	66.04	19.32	431.82	195.04
Remaining season off-peak hour (09:31 – 15:29)	91.46	8.29	1617.41	732.52	82.19	6.39	629.38	204.68
Summer peak hour (06:30 – 09:30)	85.70	17.13	2101.95	974.66	76.87	13.67	445.30	180.63
Summer peak hour (15:30 – 19:00)	80.57	21.67	2380.68	1025.11	73.14	17.90	428.27	195.55
Summer off-peak hour (09:31 – 15:29)	89.35	11.60	1553.65	747.80	80.96	9.63	597.86	201.68

Table 3. Standard deviation of the velocity and intensity of trucks in three scenarios

Time-of-the-day	St.de. Velocity	St.de. Intensity
Pick hour 1(06:30-09:30)	14.42	179.47
Pick hour 2 (15:30 – 19:00)	19.07	195.42
Off-pick hour (09:31 – 15:29)	7.47	208.73

Table 4. Simulation scenarios and baseline of A15 based on the traffic data

	Baseline_trucks (Intensity)				Scenario_platoon (Intensity)			
	Min	Mean	Max	Cars	Min	Mean	Max	Cars
Pick hour 1(06:30-09:30)	270	450	630	2633	90	150	210	2633
Pick hour 2 (15:30 – 19:00)	231	426	621	2782	77	142	207	2782
Off-pick hour (09:31 – 15:29)	411	618	828	1780	137	206	276	1780

To further explore the difference, the dataset is categorized by seasons (winter, summer and remaining seasons) and times-of-the-day within working hours (06:30 - 09:30, 09:31 - 15:29, 15:30 - 19:00). We assume that season would influence the usage of public transportation. Cars might be used more often in winter than other seasons. Peak and off-peak hours is defined according to the guidelines of the Royal Dutch Touring Club ANWB (ANWB, 2016). According to the ANWB, most commuting takes place at a certain time of the day. Table 2 shows the mean velocity and intensity by different seasons and times-of-the-day. As shown in Table 2, in winter period the intensity of cars is higher than in other seasons. However, there is almost no difference in the intensity of trucks in different seasons. The time of the day has an influence on both cars and trucks. The results indicate that there are more cars on the A15 during peak hours than the off-peak hour. The velocity is consistent with the reality that higher velocity is observed during off-peak hours of the day for both cars and trucks.

Based on the descriptive analysis, the intensity of these two vehicles can be translated into 9 scenarios considering the time of the day and intensity of trucks/platoons (the standard deviation of truck intensity). The 9 scenarios are: minimum intensity of trucks/platoons in peak hour 1, mean intensity of trucks/platoons in peak hour 1, maximum intensity of trucks/platoons in peak hour 1, minimum intensity of trucks/platoons in peak hour 2, mean intensity of trucks/platoons in peak hour 2, maximum intensity of trucks/platoons in peak hour 2, minimum intensity of trucks/platoons in off-peak hour, mean intensity of trucks/platoons in off-peak hour, and maximum intensity of trucks/platoons in off-peak hour. To avoid too many simulation scenarios, the intensity of cars for the time of the day is set as the same value based on the mean value of observed traffic situation. These scenarios take into account the variation of season effects on trucks but not on cars. The intensity of trucks is set as the baseline, and is translated to a platoon for scenarios. We assume that a platoon consists of 3 trucks with a specific inter-vehicle distance. The final scenario design is shown in Table 4.

3. Microscopic simulation set up

It is essential to building the road network according to the design and regulations of the A15 corridor. An OpenStreetMap is used as a background to establish links and connectors of the infrastructure network. The length of the traffic network is set on 1800 meters with the length of the weaving area 1000 meter, length of merging lane 180 meters, and the length of the diverging lane 120 meters. This geometry represents a typical Dutch highway network. The width of the lanes is 3.50 meters according to the guidelines of the Dutch ministry of infrastructure and environment (Rijkswaterstaat, 2016). The vehicles of the A15 are subjected to network constraints. In the Netherlands, slower vehicles are assigned to the right lane and faster vehicles to the outermost left lane. In the experiment, trucks and platoons are assigned to the right lane. Only two types of vehicles, which are cars and truck /platoons are included in the microscopic environment. The platoon in the simulation model consists of three truck with an inter-vehicle distance of 6.7 meters (69.75 meters in total) because 6.7 meters inter-vehicle distance is the most optimum fuel consumption distance (Ploeg, 2014). Longer and heavier vehicle combination (LZV) are not included in the simulation due to the fact that first standard trucks are used to establish a platoon. We assume that there is no weight difference within the platoon and as a result can be considered a homogeneous entity. All the platoons are subordinate to the 'slow lane' rule which implies that all platoons will drive on the right side of the road. The platoons are considered as SAE level 4 which indicates that there is no human intervention while driving.

In order to model the following behavior of drivers in VISSIM, the Wiedemann 99 (W99) model is used. The W99 model, comparing with the W74 model, is more suitable for freeway traffic because of the adaptability of parameters for driving behavior (Arkatkar et al., 2016; Gao, 2008). The default values are based on traffic data from German highways. Conditions at German highways can be considered as equal to conditions at Dutch highways except for the time of headway. Usually, a minimum of 2 seconds time of headway is advice on highways. However, drivers accept the smaller time of headway in the Netherlands. The time of headway is less than a second for cars and 1.3 seconds for trucks (SWOV Institute for road safety research, 2017). Therefore, we adjusted the time of headway parameter to 0.9 seconds in the simulation. To model the driving behavior considering the speed of cars and trucks, the different range should be defined based on the observation data. Considering the high traffic intensity on A15, a velocity range is set as 65.61 km/h - 105 km/h for cars and 60.71 km/h - 89.55 km/h for trucks. The maximum speed of 105km/h for cars is set for allowing the acceleration for merging or diverging. For lane changing behavior, the value for the look ahead distance near a diverging lane is set on 1200 meters. This value is based on the distance when drivers on Dutch highway are informed by signs that lane changing possibilities. For courtesy lane changing, the simulation model allows vehicles to cooperatively change lanes.

Before starting the simulation, it is necessary to validate the setup environment. To verify the input variables, 15 simulation runs are executed with different random seeds. Velocity and acceleration/deceleration speed are verified with observation data and literature. Results indicate that the simulation environment set up could represent the A15 traffic situation. To understand the impact of truck platooning on traffic management on the A15 corridor, three hypotheses are formulated which are derived from literature. These three hypotheses are translated into three criteria which can be analyzed in the simulation model as shown in Table5.

Table 5. Overview of the measurement tools for the three defined criteria

	Hypothesis	Criteria	Measurement
1)	The overall traffic flow will increase due to the presence of truck platooning;	Traffic flow	Travel time
2)	Lane changing within complex traffic situations can be affected by the short inter-vehicle distance of a platoon and a vehicle delay can occur;	Traffic efficiency	Queue delay
3)	Traffic safety near merging, diverging and weaving areas will increase.	Traffic safety	Stopped delay

4. Simulation results

Two complex areas (merging and diverging) on A15 are selected as testing areas to investigate the impact of truck platooning on traffic management. For both merging and diverging areas, there are three lines. For each area, two observation points are set as shown in the lines. One is the beginning of the area and the other is the end of the area. For each simulation, 5 runs are performed to create a more accurate output. The scenario results are compared with baselines. Results of scenario analysis at these two areas are discussed according to the criteria defined in section 3 (Table 5) in following sections.

4.1. *Traffic flow*

It is expected that platoon will increase the road capacity and therefore beneficial for the overall traffic flow on the infrastructure (Alam et al., 2015). To measure the traffic flow effect at merging and diverging areas of A15, travel time is simulated.

The result shows that platoon would increase the traffic flow by reducing the traffic time at the merging area in minimum intensity scenario for peak hour 1&2, and in minimum and mean scenario for the off-peak hour. It can be explained that merging is an exceptional maneuver and vehicles on the main road have priority compared to vehicles in the merging lane. Compulsory lane change is not taken into account in the simulation model and vehicles obey the rule that the traffic on the main road has priority compared to the vehicle on the merging lane. Therefore, it is harder for a platoon to merge in comparing to a single truck in a high-intensity scenario. At the diverging area, the platoon will reduce the overall travel time except for the off-peak hour - maximum platoon scenario, although the reduction of travel time is relatively small.

Table 6. Travel time of simulation results at merging and diverging areas

Scenarios		Merging area _travel time (seconds)			diverging area _travel time (seconds)		
		platoon	baseline	Difference	platoon	baseline	Difference
Peak hour 1	min	94	98,8	-4,8	88,5	95	-6,5
	mean	98,9	97,5	1,4	99	100	-1,0
	max	96,8	95,5	1,3	98,2	99	-0,8
Off-pick hour	min	87,5	94,5	-7,0	93,6	98,5	-4,9
	mean	96	94	2,0	97,6	98,4	-0,8
	max	94,7	94	0,7	96,8	98,6	-1,8
Peak hour 2	min	88,2	93,6	-5,4	93,8	98,3	-4,5
	mean	94	94,3	-0,3	96,5	98,2	-1,7
	max	98	94	4,0	99,3	98,8	0,5

4.2. *Traffic efficiency*

The traffic efficiency is measured by queue delay (seconds), which indicates if there is a moving bottleneck. Two queue counters were set within the network. A queue delay is registered when the velocity of all vehicles is below 50 kilometers/hour.

Table 7. Queue delay comparing platoons with trucks for different scenarios in merging/diverging areas

	Merging_end area (second)			Diverging_Lane2 (second)		
Scenarios	dif_min	dif_mean	dif_max	dif_min	dif_mean	dif_max
Peak hour 1	1,7	1,2	5,6	-0.7	1.8	4.1
Off-peak hour	1,7	3,7	3,2	-0.8	-0.9	3.4
Peak hour 2	2,0	3,2	6,9	-0.2	2.5	8.3

The result of queue delay at the merging area is presented in Table 7. The different merging value (s) is calculated by platoon scenarios value subtracting truck scenarios value. The positive difference value shows that cars cannot merge properly on the main road with platoons. The queue delay increased dramatically especially at the end of the merging area. Additionally, the queue delay increased with the rise of platoon intensity on the road, which is the off-peak hour. It indicates that merging for platoons is difficult and a suitable gap of approximately 69 meters cannot be found easily. Hence, the length of the platoon and its short inter-vehicle distance has a large impact on the merging behavior of cars but also on platoons themselves. This can increase the chance of a moving bottleneck.

At the diverging area, it is necessary to investigate the effects of the platoon on Lane2. We found the queue delay dramatically increased with the number of platoons on the road increasing as shown in Table 7. It complies with our expectation since platoons cover a large area on a traffic lane. It can be a blockage for other road traffic. 1200 meters up front the diverging lane vehicles get information if they need to diverge. The deceleration of vehicles in front of the diverging area cause a queue delay within the diverging area. Comparing the vehicle diverging behavior with the lowest intensity trucks with platoons, we found that the number of trucks and platoons perform a diverging behavior quite even at different locations within this area. However, cars performed lane change for diverging at a later point if platoons are on road comparing with trucks (Fig. 1. (b)). It indicates that the platoon has an impact on car diverging behavior.

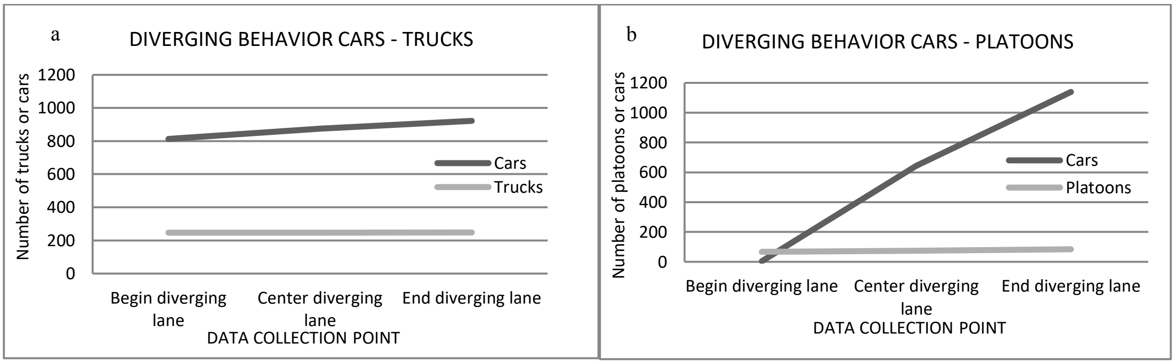

Fig. 1. (a) The number of vehicles on the diverging lane for truck scenario (b) The number of vehicles on the diverging lane for platoon scenario

4.3. Traffic safety

Traffic safety is a complicated variable to measure. A variation in speed can affect the overall traffic safety (Michalaki et al., 2016). Truck platooning can affect the driving behavior of other vehicles due to length, short inter-vehicle distance, and the variation in speed (Ferrari, 2009). In this study, the traffic safety is translated to the amount of stops vehicles need to perform in order to perform lane changes. It should be noted that this kind of behavior normally does not happen in real traffic situations, but it can indicate when vehicles want to perform dangerous maneuvers that can have an impact on the overall traffic management.

The result of stopped delay comparing platoon scenarios and truck scenarios is shown in Table 8. The different merging value (s) is calculated by platoon scenarios value subtracting truck scenarios value. The result indicates that the stopped delay happens more seriously at merging area comparing to the diverging area if platoons are on the road. For merging area, there is a less stopped delay for platoon scenarios with a minimum platoon on the roads compared with trucks. For mean intensity and maximum intensity platoon scenarios, the results show that both high car intensity and high platoon intensity will increase the stopped delay seconds. Vehicles intend to stop at the end of the merging lane. This behavior can have an influence on the gap acceptance as well as the traffic safety near this specific point. Thus, the expectation is that the traffic safety decreases as the intensity of platoons increase on the road. Traffic conflicts might arise from these stops and this can have a negative impact on the overall traffic safety.

Table 8. Stopped delay comparing platoons with trucks for different scenarios in merging/diverging areas

	Merging area			Diverging area		
Scenarios	dif_min (second)	dif_mean(second)	dif_max(second)	dif_min (second)	dif_mean(second)	dif_max(second)
Peak hour 1	-1,3	0,9	0,6	0,0	0,1	0,0
Off-peak hour	-1,0	1,4	0,9	0,0	0,1	0,1
Peak hour 2	-0,5	0,8	1,5	0,0	0,0	0,1

For the diverging area, there is a slight difference between truck and platoon scenarios. The stopped delay slightly increased in scenarios when there is a higher intensity of cars and higher intensity of trucks. Cars intend to diverge at the very last moment on the diverging lane in platoon scenarios. It may cause a variation in deceleration and acceleration behavior on the main road and ultimately reduce the overall traffic safety.

5. Conclusion

The aim of this study is to understand the impact of large-scale truck platooning. In this study, the impact of large-scale truck platooning near complex traffic locations – merging and diverging areas were analyzed. To set up a realistic foundation for the simulation, traffic data from detector loops of the A15 corridor in the Netherlands was collected and analyzed. The microscopic model VISSIM (W99) was used for the simulation. The study explored the effects of track platoon on the highway from three perspectives, which are traffic flow, traffic efficiency, and traffic safety.

To present the impacts, we organized these results by ranking on a scale from 1 to 5, based on Best-Worst-Scaling (BWS). The preferred and least preferred results are ranked according to a set of available options described below:

- *- - Severe impact*: Platooning has a severe impact on the traffic flow, efficiency, and safety. Results of the truck platoon scenario decreased by more than 50% compared to the baseline scenario (trucks);
- *- Negative*: Platooning has a negative impact on the traffic flow, efficiency, and safety. Results of the truck platoon scenario decreased by no more than 50% compared to the baseline scenario (trucks);
- *O impact is equal to the base situation*: Truck platoon did not have any effect on traffic flow, efficiency and safety compared to the baseline scenario (trucks). Extra analysis needs to be carried out to understand the full impact of platooning on a human and engineering level;
- *+ Positive:* Truck platoon increased the traffic flow, efficiency, and safety compared to the baseline scenario (trucks). The rise is within a range of 0%-25%;
- *++ Improving:* Truck platoon is beneficial for the traffic flow, efficiency, and safety. The results of the platoon scenario increased more than 50% compared to the baseline scenario.

Table 9 gives an overview of the overall conclusion of the impact of large-scale truck platooning within merging and diverging areas using the BWS.

Table 9. Overview of the impact of platooning on the traffic management at the A15 corridor

	Merging			Diverging		
	Flow	Efficiency	Safety	Flow	efficiency	Safety
Minimum intensity	+	--	++	+	+	o
Mean intensity	+	--	--	+	o	--
Maximum intensity	+	--	-	+	--	--

*Note: o Impact is equal to base situation; + Positive; ++ Improving; - Negative; -- Severe impact

The results showed that a three-truck platoon with an inter-vehicle distance of 6.7 meters and a total length of 69.75 meters has a positive influence on the traffic flow near merging and diverging areas on Dutch highways with large-scale truck platooning. It is in line with findings from the literature, which also suggested that platooning will increase the traffic flow. Results showed that with increasing of the platoon intensity, the traffic efficiency and safety decreased. Lane change performing became more difficult and spill backs occurred in the traffic locations. Especially, the lane change performance in the merging area decreased dramatically because cars cannot merge properly on the main road due to the high intensity of platoons on the road. In higher intensity platoon scenarios, queue delay occurred more frequently. Cars intended to diverge at the end part of the diverging area, which may become a dangerous behavior. For safety, only in minimum intensity platoon scenarios, the safety was not affected. However, it needs to be mentioned that the lengths of merging lane and the diverging lane were pre-defined based on the situation in the Netherlands. The different geometry road designs such as the length of these lanes might have a significant influence on the queue delay and safety. More simulation is needed to explore the impacts of road geometry designs on highway traffic, however, that was beyond the scope of this research.

It is important to mention some limitations, which should be examined in future researches. First of all, microscopic simulation models have a high level of uncertainty and it is a challenge to validate and calibrate these type of models. According to Fan et al. (2012) the parameters, which should be validated before simulations are lane changing, minimal gap acceptance, safety distance, standstill distance (CC0), headway time (CC1) and the threshold for entering 'following' (CC3). To validate the simulation environment setting it needs to be compared with real traffic data. However, the traffic data obtained cannot be used for validating these parameters. Further validation of simulation environment setting should be examined. Moreover, only two types of vehicle were taken into consideration in this simulation due to the data availability. Results of this research might be biased due to limited implementation of the driving behavior of cars and trucks. Third, it should be mentioned that the measurement of traffic safety is complicated due to the fact that numerous factors would influence on the traffic safety. Although the results showed a positive effect of safety in minimum platoon scenarios, an extensive analysis should be performed to draw a valid conclusion regarding this issue. Last, this study used the engineering factors to investigate impacts of large-scale truck platooning on Dutch highways. Human factors, especially stress, fatigue and dangerous driving behavior should be further analyzed.

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