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Experiments on Platoon Formation of Heavy Trucks in Traffic

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***Abstract*— Truck platooning is a means to significantly reduce the fuel consumption for the follower vehicle as the air drag is reduced when the inter-vehicle gap between the trucks is reduced. As each truck is assigned with different start and end locations, platoons will be frequently formed and split, while driving to their respective destinations. Additionally, the trucks are not the only ones driving on the road as there are other road users, which may influence how well a platoon can be formed. In this paper, an experimental study is conducted to investigate how traffic may affect a merging maneuver of two trucks trying to form a platoon on a public highway during rush hours. We obtained traffic data from Stockholm's motorway control system to determine the traffic condition for each test-run. Furthermore, we tried different truck speeds to study if it had any impacts on merge delay. Even in light traffic condition, a platoon merge could be delayed with over 10 % compared to the ideal case with the absence of traffic. This is partially caused by persistent drivers in which we encountered them in a fourth of the runs.**

I. Introduction

Truck platooning has become a popular topic within the transport sector as it is a means to reduce the environmental impacts significantly. Platooning, see Fig. 1, is vehicles driving close behind each other on the same lane acting as a single unit. This enables the trailing vehicles to reduce the air drag leading to lower fuel consumption and exhaust gas emissions. Additionally, by packing the vehicles close to each other, the road capacity can be increased. The vehicles in a platoon are not physically coupled, but electronically coupled through wireless communication. Platooning studies have shown that the fuel consumption can be reduced up to 20 % depending on the inter-vehicle distance among other factors [1], [2], [3], [4].

There are plenty of studies regarding vehicle platooning, such as string stability [5] where the disturbances need to be attenuated along the platoon, potential air drag reduction [1], [6], guaranteeing safety from collisions within the platoon [7], and experimental studies of fuel consumption reduction [8], [9], [10], [11] to name a few. Additionally, a platoon control can be further improved and be more fuel efficient using preview information of the road topography ahead [12], [13]. As truck platooning is closer of being a reality, little is known of the impact it has on the surrounding traffic and vice versa. The author in [14] tried to close the gap by developing a simulation platform based on microscopic traffic simulation that can be used to analyze truck platoon operations and impacts on traffic flow. The simulation experiment [15] had the purpose to study mixed traffic based on real traffic data to understand how their platooning system affects the highway traffic flow.

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Fig. 1: Three Scania trucks platooning from Södertälje, Sweden, to Rotterdam, the Netherlands, during the European truck platooning challenge.

The majority of the conducted work in vehicle platooning has mainly focused on when the numbers of vehicles in a platoon remains fixed. However, in practice, vehicles start at different locations and have different destinations meaning that platoons will be formed and split frequently. Until now, only a handful of papers consider forming platoons fuel efficiently through coordination or planning. A platoon formation can be executed by adjusting the vehicles' speeds [16], [17], rerouting the vehicles to meet and drive together [18], or by planning the transport mission and schedule the departure time such that the vehicles can travel together [19]. However, one important aspect that has been neglected is the influence of traffic and other road users. The simulation study [20] tries to capture the effect of traffic on the execution of platoon formation using a microscopic traffic simulator.

In this work, we conduct an experiment to study how traffic influences two trucks when forming a platoon in practice. Since platooning is becoming more and more relevant, coordinating and forming platoons will be more of interest. Traffic simulations, as in conducted in [20], are limited in the sense that the traffic behavior depends on the underlying model of the driver behavior, where as in an experimental study may capture aspects not covered by the traffic simulation model. One example is persistent drivers in which they drive behind the front truck and do not overtake, causing the follower truck to not be able to complete the merge. Our intention with this experiment is to obtain insights of how different traffic densities affect platoon formations and what needs to be considered when forming a platoon in practice. The traffic information is obtained through traffic measurements from already built infrastructure on the highway. This work serves as a basis and a first step for better understanding the influence of traffic on platoon formation. In the long run, one might be able to use this to build a model and predict where the trucks will merge depending on the traffic situation before executing the merging maneuver.

The main contribution of this paper is the extensive experimental study conducted on a public highway with traffic flow measurements during rush hours in order to investigate how traffic may delay a merging maneuver when forming a platoon of two trucks. We tried with different speeds for the trucks to investigate if there would be any significant differences on the merging maneuver, such as different traffic behavior. Experimental results show that even on low traffic, the merging distance is over 10 % further away than the ideal merging point. This is partially caused by persistent drivers in which we encountered them in a fourth of the runs.

The outline of this paper is as follows. In Section II, we describe and formulate our problem. In Section III, we describe the experimental setup, from the location of the experiment, to trucks and traffic measurements. In Section IV, we present the outcome of the experiment. Lastly, in section V, we conclude our work.

II. Problem description

Let us consider the following platoon formation scenario – there are two trucks, that are initially separated, driving on a highway in which their routes are partially overlapping. The trucks decide to form a platoon since the estimated saving is sufficiently large and their timing constraints would allow them to be coordinated. The remaining part of the trucks' journeys until they reach their final destinations can be split in three phases. The first is the merging phase where the trucks change their velocities in order for the rear truck to catch up with the front one. Changing the velocity is associated with a cost. The rear truck could speed up, which increases the resistive forces and leads to a higher fuel consumption, or the front truck could slow down, which either leads to a delayed delivery or that the lost time must be compensated for later by an increased velocity. The second phase is where the platooning occurs. The rear truck will experience a reduced air drag which reduces the fuel consumption significantly. Also the front truck may experience some air drag reduction. If the trucks have different destinations and/or deadlines they will need to split up at some point, after which they drive solo again. In this third phase they could make up for previously lost time, if necessary.

(a) Lead truck with trailer. (b) Follower truck.

Fig. 2: Trucks used in the experiment.

To motivate a platoon merge, the expected reward from platooning must be sufficiently larger than the expected cost of coordination. In previous work [16], fuel-optimal catch-up strategies were derived depending on the gap between the vehicles and the distance to split. This was further extended to fuel-optimal strategies on how to form platoons with two or more vehicles in [17]. However, these scenarios were studied under the ideal assumption with no traffic on the road. The simulation study in [20] considers how other road users may interrupt a merging maneuver depending on the traffic condition. In low traffic, the merging maneuver could be completed with little to no delays. As traffic got denser, the delay of merging maneuver also grew. As a truck is moving slower than the rest of the traffic, due to traffic regulations, it is considered as a moving bottleneck and will throttle the throughput of the overall traffic. The truck might therefore create congestion behind it, making it more difficult for the back truck to catch up when executing a merging maneuver.

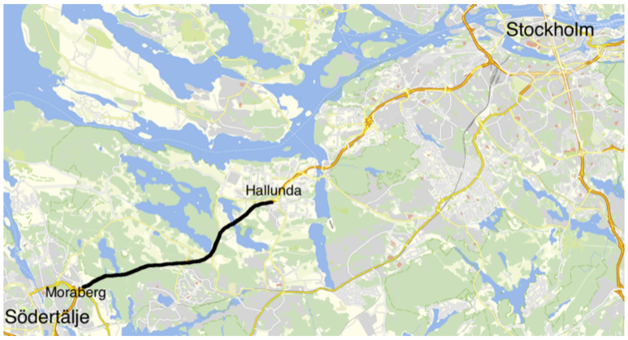
In this experiment, we focus on the first phase, the merging maneuver. The aims are to study how traffic may interfere with a merging maneuver and if different truck speeds influence the surrounding traffic behavior. Additionally, we want to compare the experimental results with the simulation study [20]. A secondary aim is to possibly complement the traffic simulation model, such as possible persistent driver that remains behind the front truck for a longer period of time making it impossible to complete a merging manuever.

III. Experimental setup

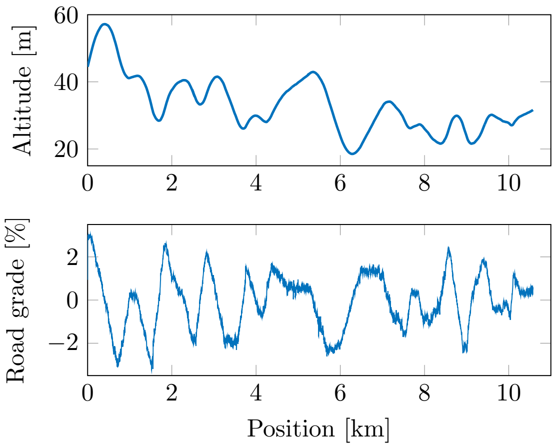
In this section, we give a detailed description of how the experiments are conducted. We divide it in three parts, the setup of the trucks, the setup of the experiments, and the traffic data from Stockholm's motorway control system (MCS).

A. *Setup of the trucks*

Two standard Scania tractor trucks are utilized as depicted in Fig. 2. The lead vehicle has a 4×2 vehicle configuration with a 480 hp engine and has a trailer with three axles. The total length of the lead vehicle with trailer is 16 m and a total weight of 37.5 t. The follower vehicle has a 6×4 vehicle configuration with a 450 hp engine and has a ballast weight. The total length of the follower vehicle is 6 m and a total weight of 15 t. Both vehicles have standard commercially available equipments, which include doppler radars, global



(a) Location of the experiment.



(b) Altitude and road grade of the road in the northbound direction.

Fig. 3: The experiment took place between Hallunda and Moraberg, southwest of Stockholm, Sweden.

positioning systems (GPSs), front looking cameras (FLCs) and electronic control units (ECUs). A data logger and an additional camera are installed in each vehicle to record and log the experiments. The data logger is directly connected to the truck's internal controller area network (CAN) and reacts to ignition's on and off to respectively start up and shut down the data logger. The additional camera is installed to record the view in front of the truck as the FLC is not used for such purpose. We use the doppler radar to measure the relative speed and distance to the vehicles in front. The FLC is used to detect objects in front of the truck including vehicles and lane markings on the road. The FLC is able to classify the objects it detects into two-wheeler, car, truck, or unknown depending on the estimated width of the objects. The GPS is used to localize the truck on the highway and to sync the time between the lead and follower vehicle.

B. Experiment location and scenarios

The experiments are conducted on the E4 and E20 highway between Hallunda and Moraberg, which are located between Stockholm and Södertälje, as shown in the map of Fig. 3a. The top plot in Fig. 3b shows the altitude profile and the bottom plot the corresponding road grade profile. As shown by the road grade profile, the road is fairly hilly with road grade segments of $\pm 3\,\%$. The highway is a three-lane road with a total length of 11 km and a fixed speed limit of 100 km/h. Trucks are only allowed to drive on the middle and the rightmost lanes. Additionally, there is an on- and off-ramp approximately in the middle of the highway stretch (at Salem). The number of cars that enters and leaves at this location is relatively low throughout the day. The experiments took place during four weeks in November 2015. Both vehicles start on the same location at one end of the road, just outside the highway. The lead vehicle starts driving and enters the highway while the follower vehicle waits approximately 40 s in order to open a gap. This corresponds to approximately 800 m that the follower vehicle needs to catch up. The experiment starts when the follower vehicle enters the highway. The drivers are instructed to drive with adaptive cruise control (ACC) with a desired speed and they are allowed to overtake vehicles if needed. Once the follower vehicle catches up to the lead vehicle, they platoon until they reach the other end of the highway stretch. We refer to one such north- or southbound drive as a test-run. The test-runs are conducted during the rush hours, i.e., between 6:00–10:00 in the morning and 14:00–18:00 in the afternoon in order to capture a set of different traffic densities. During the three first days, the afternoon shift was between 15:00–19:00. Three merging maneuver speed pairs are considered, namely (75,85), (75,89), and (80,89) km/h, where (v_1,v_2) denotes the speed of the lead and follower truck, respectively. We refer to one such pair as a test-scenario. The choice of test-scenarios is due to traffic regulations and not wanting to deliberately congest the highway by driving too slow during rush hour. The speeds are set as the desired speed of the ACC, together with a downhill speed control (DHSC) offset of 5 km/h. The DHSC enables the truck to accelerate on descents and gain speed until the vehicle speed reaches the offset in which the system intervenes by applying brakes to not overspeed.

C. Stockholm's MCS traffic data

Traffic data are obtained from Stockholm's MCS during the experiment. The collected data are from the time the experiments were conducted, i.e., between 6:00–10:00 and 14:00–19:00 for twenty weekdays. The traffic data are based on measurements from microwave detectors (doppler radars). Each detector measures the number of passing vehicles and the harmonic mean speed within one-minute time intervals. The microwave detectors are mounted on gantries along the highway as shown in Fig. 4, one detector for each lane. The gantries are placed 200–400 m from each other along the highway. There are a total of 41 and 37 gantries in the north- and southbound directions, respectively, between Moraberg and Hallunda. Each gantry is paired with two outstations, see Fig. 4 on the left. These outstations connect the gantries with a central system that collects traffic data and change the variable speed limit (or message) sign according to the gathered traffic data and traffic situation.

IV. Results

In this section, we first evaluate the merging maneuver and how different traffic condition influences it. Then, we

Fig. 4: Each gantry of Stockholm's MCS is equipped with microwave detectors (behind the variable speed limit sign) that measure traffic flow and harmonic mean speed on each lane. The big white bulk on the left is an outstation, which connects two gantries with a central system.

TABLE I: A break down of all the test-runs that are conducted in test-scenarios and directions. Successful merging maneuver are presented in parentheses.

Direction \ Scenario	(75,85)	(75,89)	(80,89)	Total
Northbound	88 (77)	87 (81)	97 (73)	272 (231)
Southbound	75 (71)	83 (77)	89 (68)	247 (216)
Total	163 (148)	170 (156)	186 (141)	519 (447)

investigate how often car drivers are in between the two trucks and are reluctant to change lanes, which is often a reason for a delayed platoon formation.

A. *Successful and failed test-runs*

In total, there are over 600 test-runs conducted during the four weeks. However, due to traffic accidents and data corruptions some of the data set is filtered away. We end up with 519 test-runs, where 447 of these test-runs are successful formations of a platoon. Table I summarizes all the test-runs and breaks them down into test-scenarios and directions. Furthermore, we only consider test-runs where the initial distance between the two trucks is between 400 to 1300 m. To classify a successful merging maneuver, three criteria need to be satisfied:

1) The relative distance between the merged trucks, based on their GPS positions, must be less than 80 m,
2) The doppler radar must detect a moving object in front of the vehicle, with a similar relative distance as the GPS measurements,
3) The FLC must detect an object in front of the vehicle and classify the object as an truck.

The 72 failed attempts to merge are due to a too large initial distance combined with a limited road length, highly congested traffic condition, or cars persistently driving behind the lead truck making it impossible to satisfy all three criteria and complete the merging maneuver. The explanation behind a too large initial distance combined with a limited road length is that during the first week of the experiment (the (80,89) km/h test-scenario), there was road construction work near the entrance to the on-ramp on the northbound direction. The road construction work caused the trucks to

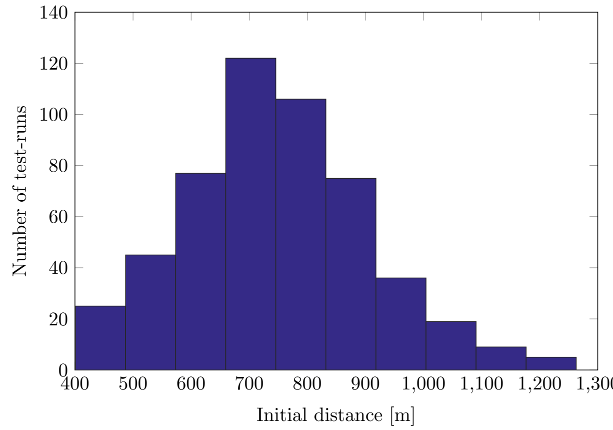
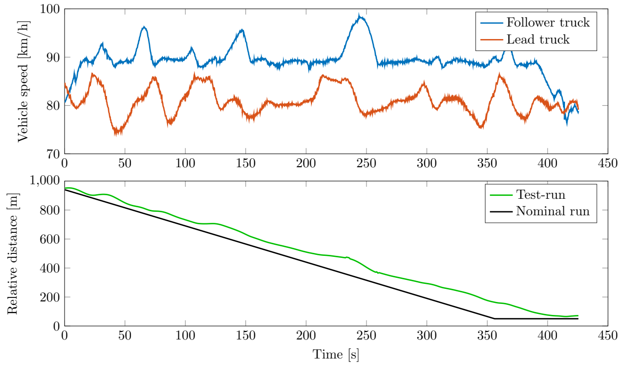


Fig. 5: The frequency of different initial distances for all test-runs. The average initial distance is 748 m.

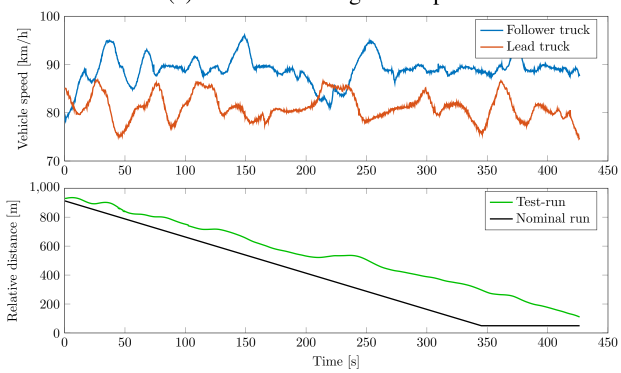
enter the highway with different timing, which resulted in sometimes large initial distance. Fig. 5 shows all the initial distances between the vehicles as the follower vehicle entered the highway. Note that a failed merging maneuver in this experiment means that the trucks did not manage to merge before the end of the stretch where the vehicles need to exit. There are over 30 test-runs where the initial distance is larger than 1 km. This makes it very difficult to complete a merging maneuver for the (80,89) km/h test-scenario as it takes 10 km to merge and the road length is only 11 km. Highly congested traffic causes the follower vehicle to have difficulties to change lanes and overtake other cars to catch up with the lead vehicle. Persistent drivers are discussed in the following section.

B. *Two examples*

The results for two test-runs over the northbound direction for the test-scenario (80,89) km/h are shown in Fig. 6. Each example consists of a speed profile plot and a relative distance plot. The large speed fluctuations are mainly due to the road topography, cf., Fig. 3. In the first example in Fig. 6a, the trucks start approximately 950 m apart from each other. The follower vehicle catches up to the lead vehicle just before they reach the end of the road stretch. The test-run is compared to the nominal run, where the merge is completed 50 s later than the nominal run, which is due to minor disturbances from other traffic. The nominal run is the theoretical run where the trucks keep a constant desired speed and platoon once the relative distance is 50 m. In the second example in Fig. 6b, the trucks start with a similar initial distance. However, along the way the follower vehicle cannot maintain its speed due to other road users, which forces the follower vehicle to slow down (at around 200 s and 270 s). From there, the relative distance is too large for the follower vehicle to catch up with the lead vehicle before the end of the road stretch that is used in the experiment and therefore this test-run failed to form a platoon. Note that the failure in this case would have completed the platoon formation if we allowed the vehicles to drive a bit further.



(a) Successful merge attempt.



(b) Failed merge attempt.

Fig. 6: Two examples of test-runs with speed profiles and relative distance. The nominal run corresponds to both trucks drive constantly at their set speeds and platoon once the relative distance is 50 m. The first (top) example shows the follower vehicle barely had any disturbances from surrounding traffic and could merge successfully. The second (bottom) example shows that there were some influence from surrounding traffic that made the follower vehicle drop in speed both at 200 s and 270 s and could therefore not complete the merging maneuver before the end of the highway stretch.

Traffic data and fundamental diagram

Traffic data from the MCS are gathered to understand in what the traffic condition is during the merging experiments. Fig. 7 shows the fundamental diagram using all data points collected during the entire experiment period and over the whole road length. One blue dot represents an aggregated minute of three microwave detectors together that are mounted on the same gantry, i.e., a one-minute gantry measurement. There are in total over 830 000 gantry measurements in Fig. 7. The fundamental diagram here is similar to the fundamental diagram from the simulations in [20], if the outliers (low traffic flows with low traffic density), mainly caused by accidents, are ignored. The maximum flow is approximately at 2 100 veh/h/lane with a corresponding traffic density at 22 veh/km/lane, resulting in a mean speed of 95 km/h. The free flow branch is slightly more outspread compared to the simulated fundamental diagram. Similarly,

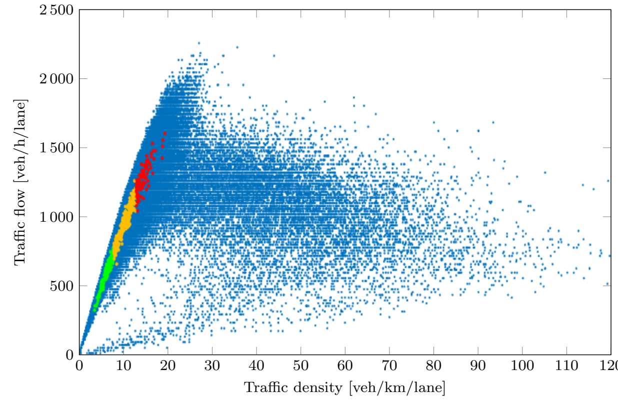


Fig. 7: Fundamental diagram based on the traffic sensor measurements during the entire experiment period. The green, yellow, and red colored dots represent the traffic conditions (light, medium, and heavy traffic) during the merging maneuver experiments.

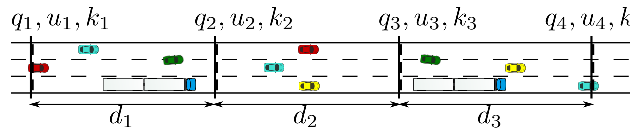


Fig. 8: An illustration of three-lane highway with gantry measurements. We assume the ith gantry measurement (flow q_i, mean speed u_i, and density k_i) holds for the next d_i distance until the next gantry, $i+1$.

the congestion branch is more outspread but also slightly lower compared to the simulated fundamental diagram. To calculate the traffic density for each test-run, we assume each gantry measurement is constant until the next update and holds along the road until the next gantry on the road, as seen in Fig. 8. Gantry i measures flow q_i, harmonic mean speed u_i, and density k_i each minute and the distance to the next gantry, $i+1$, is d_i. The traffic density for each test-run is calculated as soon as both trucks are on the highway. We consider a weighted traffic measurement (based on d_i) from the gantry measurement behind the follower vehicle to the gantry measurement behind the lead vehicle, which in Fig. 8 are gantries 1 to 3. The traffic densities for each test-run during the experiment are depicted in Fig. 7 with green, yellow, and red colored dots and varies from 3.5–19.5 veh/km/lane. We divide the test-runs into three categories according to the traffic density. The green dots represent light traffic (lower than 8 veh/km/lane), yellow represents medium traffic (between 8 and 13 veh/km/lane), and red represents heavy traffic (above 13 veh/km/lane). There is a total of 164, 266, and 89 test-runs for light, medium, and heavy traffic, respectively.

Outcome of merge distance

For each test-run, we compare the outcome when the trucks managed to form a platoon with the nominal run, by normalizing the test-run with the nominal run. The nominal run is when the vehicles maintain their desired speeds and

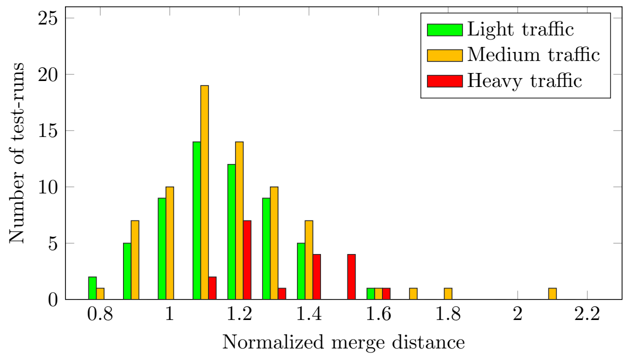


Fig. 9: Histogram of the (75,85) km/h test-scenario over the actual outcome of merge distance normalized with the nominal merge distance. Values below 1 indicates minor interruption by surrounding traffic on the lead truck leading to a shorter merge distance.

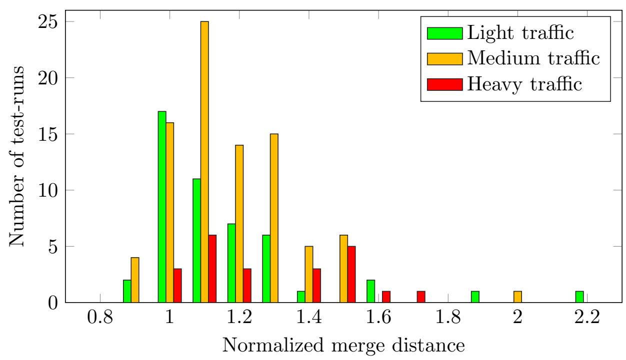


Fig. 10: Histogram of the (75,89) km/h test-scenario over the actual outcome of merge distance normalized with the nominal merge distance.

merge at $d_m = d_s v_2/(v_2 - v_1)$ distance from where the follower vehicle starts. We plot the results for each test-scenario in a histogram with each traffic category. Figures 9–11 and Table II summarize all the test-scenarios and test-runs. The histograms show that there are a few test-runs that where the merge occurs earlier than the nominal run (below value 1) and a few test-runs where the trucks drive twice the distance to merge. The earlier merge (compared to the nominal run) indicate that there are cars in front of the lead vehicle causing it to drive slower, thus the platoon is formed earlier. There are also a few test-runs in light and medium traffic that failed to merge. This is mainly due to persistent drivers that keeps driving behind the lead truck and do not change lanes. Lastly, for all three figures, we see a slight shift in the bars for heavier traffic, indicating that the merging maneuver is slightly prolonged with higher density. This is more evident in Table II where the mean value of the normalized merge distance is shown for each test-scenario. The mean value of the normalized merge distance increases with higher traffic density.

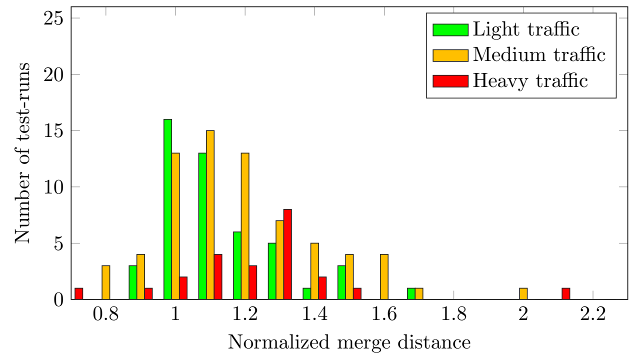


Fig. 11: Histogram of the (80,89) km/h test-scenario over the actual outcome of merge distance normalized with the nominal merge distance.

TABLE II: A summary of all the test-scenarios and test-runs conducted. The minimum, maximum, mean, and standard deviation (std) are indicated for all test-scenarios.

Test-scenario and traffic case	Test-runs		Normalized merge distance			
	total	successful	min	max	mean	std
(75,85) km/h light	59	57	0.85	1.56	1.14	0.16
(75,85) km/h medium	83	72	0.79	2.10	1.17	0.21
(75,85) km/h heavy	21	19	1.10	1.61	1.33	0.17
(75,89) km/h light	48	48	0.90	2.19	1.16	0.24
(75,89) km/h medium	94	86	0.93	1.99	1.18	0.18
(75,89) km/h heavy	28	24	1.03	2.60	1.39	0.39
(80,89) km/h light	57	48	0.93	1.66	1.13	0.17
(80,89) km/h medium	89	70	0.83	1.97	1.19	0.23
(80,89) km/h heavy	40	23	0.74	2.10	1.24	0.26

Persistent drivers

In general, there are drivers that are reluctant to change lanes. This is often not an issue since other cars can change lanes and overtake the reluctant driver. However, for a platoon formation case, these reluctant drivers may be an issue as they may hinder the completion of a platoon formation if they insist driving behind the lead truck. We call these drivers for persistent drivers. We define the existence of a persistent driver when it takes over 1 km to complete the merge once the trucks are less than 80 m from each based on the GPS measurements. In other words, there is a persistent driver that drives behind the lead truck when it takes over 1 km drive from that the first criterium of successful merging maneuver is satisfied until all three criteria are satisfied. Fig. 12 shows an example where the relative distance between the trucks goes below 80 m at time 255 s. However, as there is a vehicle in between the trucks, the merging maneuver is never completed. Video records confirm that there is a car driving in between the trucks. Table III summarizes the results for all test-scenarios. There is a persistent driver in 24 % of the total test-runs and they are the reason behind half of the failed merge attempts in total. This indicates that the possibility of persistent drivers need to be considered in a platoon formation.

V. Discussion and Future Work

The outcome of the experiments indicates that traffic has an impact on the platoon formation and merge distance com-

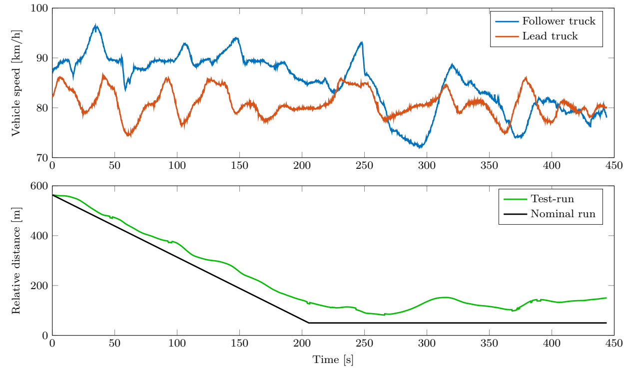


Fig. 12: An example of a test-run with a persistent driver. The relative distance between the trucks is below 80 m at time 255 s but due to a car in between, the merging maneuver is incomplete.

TABLE III: The number of persistent drivers that cause either delayed merge or failed attempts.

Test-scenario and traffic case	Total test-runs	Persistent drivers total	Persistent drivers caused failure
(75,85) km/h light	59	13	0
(75,85) km/h medium	83	22	5
(75,85) km/h heavy	21	7	1
(75,89) km/h light	48	4	0
(75,89) km/h medium	94	21	7
(75,89) km/h heavy	28	9	2
(80,89) km/h light	57	13	5
(80,89) km/h medium	89	19	9
(80,89) km/h heavy	40	18	6

pared to the nominal case, which aligns with the simulation study conducted in [20]. However, the merge delays may differ as the premises differ. The first truck may also get affected by traffic, which causes the first truck to drive slower that leads to a shorter merge distance. Although this may sound plausible, one aspect that is not considered is the traffic in front might be too dense to begin with, meaning that the follower truck would have caught up anyway without speeding up. Another aspect may be that the formed platoon might not be able to maintain its desired speed, leading to a delayed transport. Another outcome from the experiments is that persistent drivers are quite common on the highway, where they are either reluctant to change lanes and overtake trucks or they are comfortable driving at a lower speed behind a truck. The choice of the test-scenarios is an attempt to also study if (persistent) car drivers have more incentive to change lanes when the truck is driving slower at 75 km/h on the highway. Unfortunately, the outcome of the results do not indicate such behavior. Furthermore, persistent drivers are not the only one affecting a platoon formation, as other trucks on the highway may also affect it. The other trucks may drive slower, which causes our own truck to drive as slow and consider overtaking if the speed is too low. This results in a longer merge distance and needs to be considered before executing a platoon formation.

As this work serves as a first step towards better understanding of the influence of traffic on platoon formation, there are plenty of possible extensions. This include an analytic model to predict merge distance, improve driver behavior in traffic simulation tools for this kind of studies, and study persistent drivers further and propose actions to avoid them with many more. All these are left as future work.

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