

The Influence of Traffic on Heavy-Duty Vehicle Platoon Formation

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Abstract—Heavy-duty vehicle (HDV) platooning is a mean to significantly reduce the fuel consumption for the trailing vehicle. By driving close to the vehicle in front, the air drag is reduced tremendously. Due to each HDV being assigned with different transport missions, platoons will need to be frequently formed, merged, and split. Driving on the road requires interaction with surrounding traffic and road users, which will influence how well a platoon can be formed. In this paper, we study how traffic may affect a merging maneuver of two HDVs trying to form a platoon. We simulate this for different traffic densities and for different HDV speeds. Even on moderate traffic density, a platoon merge could be delayed with 20 % compared to the ideal case with no traffic.

I. INTRODUCTION

The demand for transportation is continuously increasing – people are constantly on the move and goods need to be transported worldwide in order for the world economy to keep running – and is expected to keep growing. More cars and heavy-duty vehicles (HDVs) on the road mean more greenhouse gas emissions which affects the environment negatively. With predictions of rising demands for transports, the European Commission has set goals towards a more competitive and resource-efficient transport system. The key goal is to cut the emissions in the transport sector with 60 % by 2050 in order to reduce the environmental impacts to avert climate change and maintain a sustainable environment [1]. With road freight transport corresponding to 72 % of the total CO₂ emission within the transport sector in Europe [2], both HDV manufacturers and fleet owners face difficult challenges for a maintained sustainable environment. Fortunately, in the past decade, the technology development in the vehicle industry has grown rapidly and has enabled solutions to reduce the environmental impacts. Highly optimized engines and drivelines, hybrid vehicles, waste heat recovery, light weighted cars, and convoy driving are just a few approaches for a more sustainable environment.

One of the advances that has shown great potentials to significantly reduce the fuel consumption and emissions as well as increase the traffic throughput is convoy driving, also known as vehicle platooning (see Fig. 1), which is vehicles



Fig. 1. Two HDVs platooning with almost no traffic.

driving close behind each other on the same lane acting as a single unit. Forming platoons can be achieved with the help of cooperative adaptive cruise control (CACC), which is an extension of adaptive cruise control (ACC). The ACC is a radar-based system that enables the vehicle to maintain a desired speed set by the driver while driving at a safe distance to the vehicle ahead. CACC extends this further by equipping the vehicles with wireless communication, allowing the vehicles to communicate with neighbouring vehicles (also equipped with CACC) as well as vehicles further away. This enables vehicles driving even closer yet at a safe distance, a smoother drive and (almost) instantaneous reaction in case of emergency.

Studies have shown that HDV platooning can reduce the fuel consumption with up to 20 % [3], [4], [5], [6] depending on the inter-vehicle distance among other factors, due to reduced air drag that the trailing vehicle experiences when driving in a platoon. Alam et al. [7] evaluated the fuel savings of HDV platoon in practice and showed a saving of 6.5 % driving at highway speed with 1 s time gap. Studies using traffic simulation models have shown that ACC/CACC, depending on the penetration rate, has a positive effect on the traffic with decreased shockwave effects, smoother drive, and higher average speed [8], [9], [10], [11], [12]. In a recent paper [13], Deng and Ma studied the impacts HDVs platooning with CACC has on mixed traffic, both in the fuel consumption and travel time, using a microscopic traffic simulation tool. The study showed that when the HDV penetration rate is higher than 40 %, the fuel savings are substantial meanwhile the positive impacts on the overall traffic are preserved.

The majority of the conducted work in vehicle platooning

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has mainly focused on the impacts when the vehicles start and remain in a platoon throughout the trip. However, in practice, vehicles start at different locations and have different destinations meaning that platoons will be formed and split frequently. Many studies have been conducted on how vehicles should enter or leave platoons in traffic on on- or off-ramps [14], [15], [16] with focus on execution and performance rather than fuel efficiency. Until now, there have only been a handful of papers considering forming platoons fuel efficiently through coordination or planning. A platoon formation can be done by adjusting the vehicles' speeds on the fly [17], [18] (i.e., one vehicle catches up on the other), or by rerouting the vehicles to meet and drive together [19], or by planning the transport mission and schedule the departure time so the vehicles can travel together [20]. However, one important aspect that has been neglected is the influence of traffic and other road users.

In this work, we study how two HDVs interact with the rest of the traffic when forming a platoon. Since platooning is becoming more and more relevant, coordinating and forming platoons will be more of interest. It is therefore essential to have an insight of not just how platoons affect the traffic but also how coordinating and forming platoons affect the traffic and vice versa. Many studies, mentioned earlier, have focused on the first part, while the latter has been left open. By platoon formation, we mean two vehicles adjusting their speeds (from their original speeds) to merge and form a platoon. Our intention with this study is to obtain insights of how traffic affects platoon formations. Traffic may affect a platoon formation in the sense that it might take longer to form the platoon, or might completely interfere the formation making it not feasible to form the platoon anymore. This paper serves as a first step towards a better understanding. In the long run, one might be able to predict the consequences of the platoon formation given the traffic situation before executing the merging maneuver.

The main contribution of this paper is to investigate how the traffic density of the surrounding traffic may delay a merging maneuver of forming a platoon of two HDVs depending on the traffic density. It is pretty clear that when there is no traffic, a platoon formation can be executed more or less flawlessly, while it is impossible in a traffic jam. However, it is not clear in between the two phases, therefore this paper serves as a first step to grasp a better understanding of the influence of traffic on platoon formation. We simulate for different speeds that the HDVs merge and for different traffic densities up to the density corresponding to the maximum traffic flow. Simulation results show that even on medium traffic, the merging distance will be 20% further away than the ideal merging point.

The outline of this paper is as follows. First, in Section II we describe our problem. In Section III, we describe the microscopic traffic simulation tool that we used and how we setup our experiment. We then present the simulation results in Section IV. Lastly, in Section V we conclude our work and give an outlook for future work.

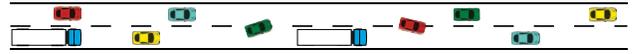


Fig. 2. Two HDVs driving solo on a two-lane road with surrounding traffic.

II. PROBLEM DESCRIPTION

Let us consider the following platoon formation scenario: there are two HDVs initially separated driving on a highway segment as depicted in Fig. 2. The vehicles decide to form a platoon since the predicted savings of platooning will be higher than the cost of executing a merging maneuver. In previous work [17], fuel-optimal catch-up strategies were derived depending on the inter-vehicle distance and the distance to split, so called the distance ratio. This was further extended to fuel-optimal strategies on how to form platoons with two or more vehicles in [18]. However these scenarios were studied under the ideal assumption of no highway traffic influencing the platoon formation. The problem considered in this paper is to investigate how other traffic may influence platoon formation. When forming a platoon with (almost) no traffic, then the platoon formation can be executed flawlessly and as planned. The other extreme is congested traffic, then the platoon formation is impossible to execute and the HDVs just follow the traffic flow. This occurs when the road reaches its maximum traffic flow. The interesting aspect is between these two traffic conditions, namely when there is traffic that might influence the platoon formation.

There are two aspects of interest: how does the traffic flow affect the timing of a merging maneuver and is there an optimal speed to form the platoons depending on the traffic condition, especially the slow down speed of the lead HDV. Driving very slow might create a large bottleneck behind the lead HDV making it more difficult for the trailing vehicle to complete the merging maneuver but for a short time. Driving just a bit slow might create a smaller bottleneck but for a longer time. Whichever strategy is more preferred is unclear and will be studied here. To do this, we simulate for different traffic densities as well as different slow down speeds of the lead vehicle in order to analyze if there is an optimal platoon formation speed depending on the traffic conditions.

III. METHODOLOGY

In order to investigate how the interaction between a merging maneuver and traffic is, a simulation tool is required. We used the microscopic traffic simulation tool from [13], which we will describe briefly here. We kindly address the reader to read the paper for more in-depth information about the simulation platform. We then describe the merging maneuver and the setup we used for our simulations.

A. Simulation Model

The framework of the simulation platform is implemented using C++ and VISSIM COM server. The framework consists of four major components: simulation engine VISSIM [21], user input interface (UII), vehicle generator (VG), and vehicle state updater (VSU). The work flow of the framework is depicted in Fig. 3. First, we have the UII where we

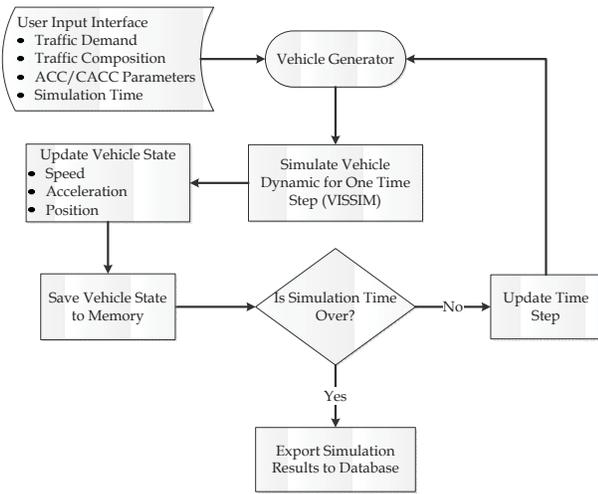


Fig. 3. Work flow diagram of the simulation platform.

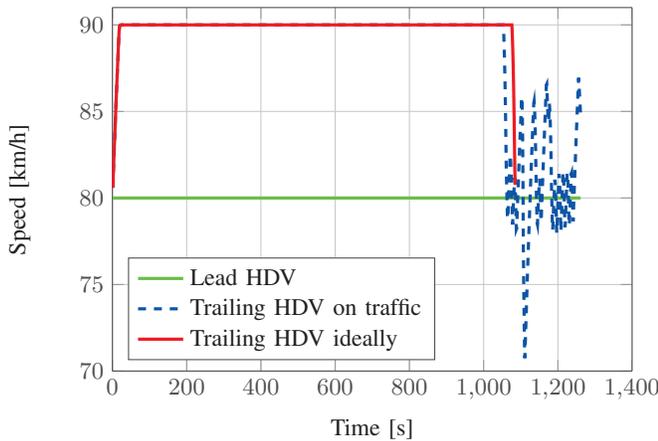


Fig. 4. A catch-up scenario where the HDVs are initially 3 km apart. Ideally when there is no traffic, a merging maneuver would take approximately 1080 s. However, when there is traffic, cars can be driving in between or cut in which can disturb (as shown in Fig. 5) and delay the platoon formation. In this example, the platoon formation was delayed with almost 200 s.

set how the simulation should run – the simulation time, traffic demand, desired speeds of the vehicles, ACC/CACC parameters, etc. This triggers the VG, which overrides VISSIM’s vehicle generator mechanism and loads traffic demand according to the UI. VISSIM plays an important role in simulating vehicle dynamics by its psycho-physical car-following and lane-changing behavior. The state of each vehicle will be recorded by VSU. This component tracks speed, acceleration, and position of each vehicle unit and updates traffic information, e.g., density, space mean speed, and traffic flow every simulation step. The simulation results are presented once the simulation run is completed.

B. Merging Maneuver

In order to form a platoon of two separated HDVs, a merging maneuver is required. Consider a catch-up scenario

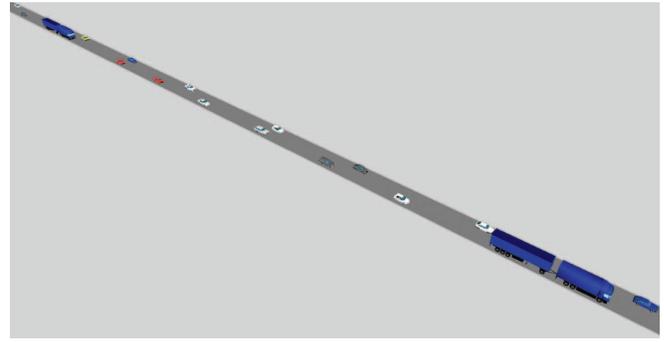


Fig. 5. A pair of HDVs trying to form a platoon, however cars are driving in between makes it difficult to complete the merging maneuver.

where the trailing HDV speeds up from 80 km/h to 90 km/h¹, while the lead HDV maintains 80 km/h. Ideally, when there is no traffic, the trailing HDV will accelerate and maintain 90 km/h without any issues. Once it is close to the lead HDV, it will start to decelerate to match the speed and then platoon. This whole process would take approximately 1080 s if the HDVs were initially 3 km apart, see Fig. 4 for illustration. However, when there are also cars driving on the road, the cars might interrupt the merging maneuver of the HDVs. In Fig. 4 (blue dashed line) and Fig. 5, the trailing HDV has no problem maintaining 90 km/h until it gets close to the lead HDV. Cars have piled up behind the lead HDV making it difficult to complete the merging maneuver, and this forces the trailing HDV to accelerate and decelerate due to cars cutting in or changing lanes. The trailing HDV gets slowly closer and can finally complete the merge when all the cars in between have changed to the left lane, which delayed the platoon formation with almost 200 s.

C. Setup

To examine how a merging maneuver of a platoon formation interacts with the traffic, we made our simulations on a 50 km long straight two-lane road. In order to know when there is traffic on the road, we simulated only cars on the road with different traffic densities to establish the fundamental diagram depicted in Fig. 6. The desired speed of the passenger cars follows a normal distribution with a mean value of 110 km/h and standard deviation of 8 km/h. From Fig. 6 (top), we can note that the maximum traffic flow is approximately 1650 veh/h/lane which corresponds to a traffic density of 19 veh/km/lane. At maximum flow, the space mean speed of the vehicles is 87 km/h. Once beyond the maximum flow, the space mean speed drops quickly. At low space mean speed (and heavy traffic density), the platooning effect is not that significant. We will therefore look at traffic densities up to the density corresponding to the maximum traffic flow where the traffic situation is of interest to study.

To study how a merging maneuver is affected by the surrounding traffic, we simulate different speeds of the HDVs and different traffic densities. Both vehicles are driving on the right lane of the road as depicted in Fig. 7 and are initially

¹The maximum allowed speed for HDVs in Europe is 90 km/h.

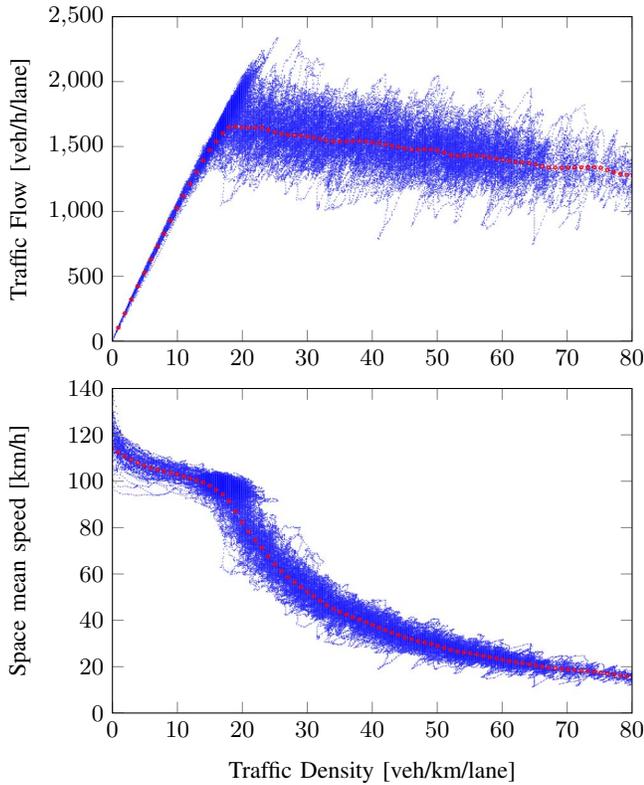


Fig. 6. The fundamental diagram of the two-lane road with a maximum traffic flow of 1650 veh/h/lane, which corresponds to traffic density of 19 veh/km/lane. The blue data points are the simulated results while each red data point is the average of all blue data points between i and $i + 1$ where i is an integer number of the traffic density.

3 km apart. The trailing HDV will drive at 90 km/h in order to catch up with the lead HDV. The lead HDV will slow down with different speeds in order for us to analyze how the merging maneuver is affected by the surrounding traffic and the time to form a platoon. For example, slowing down to 50 km/h will most likely create a bottleneck behind the lead HDV which will interrupt the merging maneuver for a while, or driving at 80 km/h might cause smaller disruptions in the traffic flow but for a longer time. We will simulate slow down speeds of 80, 75, and 70 km/h for the lead HDV. We define that the merging maneuver is complete and that the HDVs are platooning once the inter-vehicle distance is less than 30 m and there are no cars in between, which is also where the simulation will stop. We will measure the distance it takes for the vehicles to merge and form a platoon as well as the average speeds both vehicles maintained. We compare this to the ideal case², which can be easily calculated by the distance to "collision" for constant speeds. The ideal merging distance d_m (from the perspective of the trailing vehicle) is defined as $d_m = d \cdot v_2 / (v_2 - v_1)$, where d is the initial gap, v_1 and v_2 the speed of lead and trailing HDV, respectively. We had a 3 km long warm up stretch where we first simulated

²Note that the ideal case assumes that the vehicles are point-masses and that they collide, while in reality the vehicles have length and drive with a safe inter-vehicle distance which are not considered.

the cars for a short period of time to create the desired traffic density before loading the two HDVs on the road. The traffic densities we chose to simulate were approximately 11, 15, and 19 veh/km/lane, which we define them as light, medium, and heavy traffic, respectively. For each scenario and case, we simulated 30 times.

IV. RESULTS

The result of the simulations are depicted as box plots in Fig. 8 and 9. The notation (v_1, v_2) stands for the lead vehicle's speed v_1 and the trailing vehicle's speed v_2 . On each box, the red line inside the box is the median of the resulting data, the edges of the box are the 25th and 75th percentiles of the data, and the end of the whiskers outside the box indicates the maximum and minimum value of the data. We also included each individual simulation result with purple "x".

For the merging distance, as depicted in Fig. 8, it occurred later than the ideal merging distance (depicted with green squares) for all cases. The ideal merging distances for (70,90), (75,90), and (80,90) km/h cases are 13.5, 18, and 27 km, respectively. Starting with medium traffic, the merging distance increased with 46%, 37%, and 20% respectively, in average compared to the ideal case. This is mainly due to that the lead HDV creates a bottleneck behind it as seen in Fig. 5, and as the velocity difference between the two lanes (the left lanes drives much faster) increases, the more difficult is it for the cars behind the lead HDV to change lanes. Therefore a larger bottleneck will be created as the lead HDV drops more in speed. This in turn will affect the trailing HDV's ability to merge, since there will be cars in between. This will affect the average speed for the trailing HDV negatively, which can be noted in Fig. 9. The average speed for the lead HDV was within $[-0.2, 0.8]$ km/h from the desired speed for all cases. For heavy traffic, the merging point gets increased even further due to even more cars on the road interrupting the merging maneuver. The merging distance increased with 66%, 58%, and 45% in average for (70,90), (75,90), and (80,90) km/h cases, respectively. For light traffic, the merging distance only increased between 4 – 5% in average. However, note that the range of the trailing HDV's speed for (70,90) km/h case is around 4 km/h for all traffic scenarios and this is due to (as earlier mentioned) the bottleneck the lead HDV creates by slowing down.

We can note that the delayed merging point and lowered average speed for the trailing HDV is mainly due to the cars in between the two HDVs. Cars will change lanes and cut in, making the trailing vehicle to accelerate and decelerate (as seen earlier in Fig. 4). However, the slower the lead HDV drives, the more difficult it is for the cars behind it to change lanes due to the big difference in speeds between the two lanes. This could be noted as the merging point occurred much later (in percentage), which essentially means that the HDVs will not be able to platoon as much time as planned, leading to reduced fuel savings. However, if the cars were driving slower due to for example speed limit,

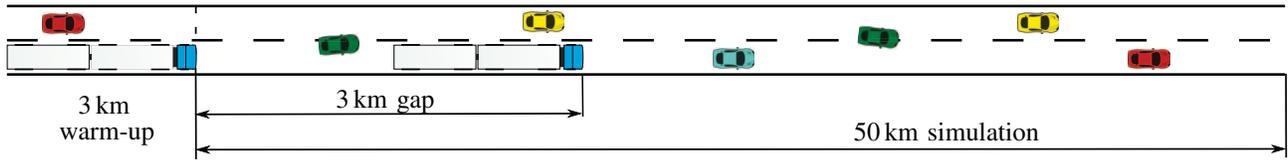


Fig. 7. The simulation setup, where the HDVs are initially 3 km apart from each other driving on a 50 km long road.

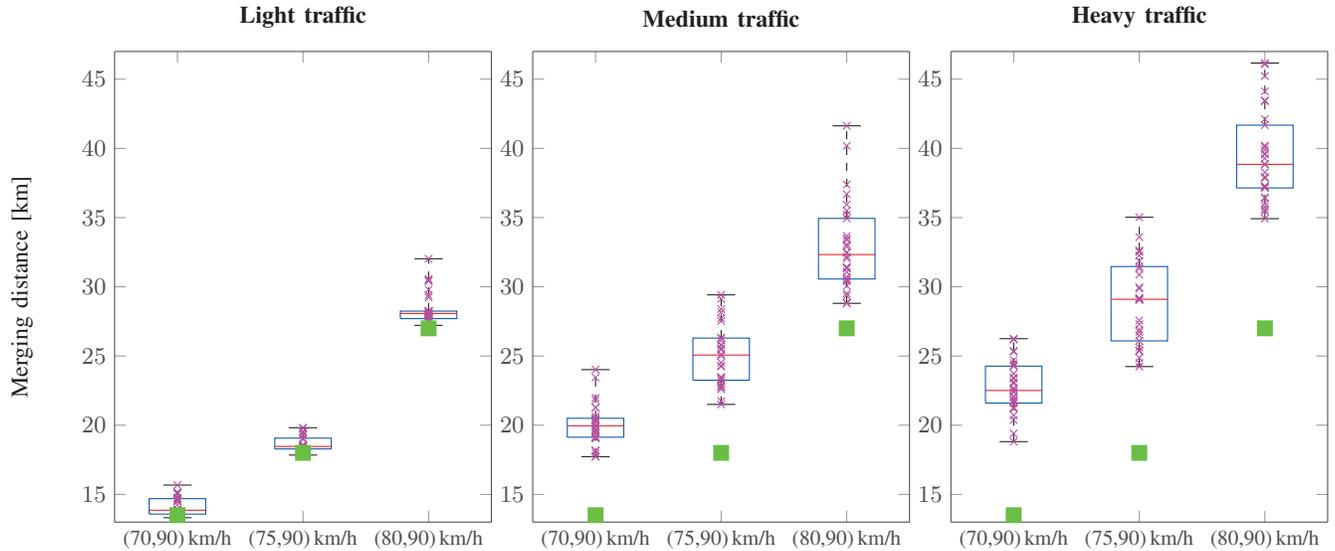


Fig. 8. Box plot of the merging distances for light (left), medium (middle), and heavy traffic (right). Each individual simulation result are plotted with purple "x". The ideal merging distances are depicted with a green square.

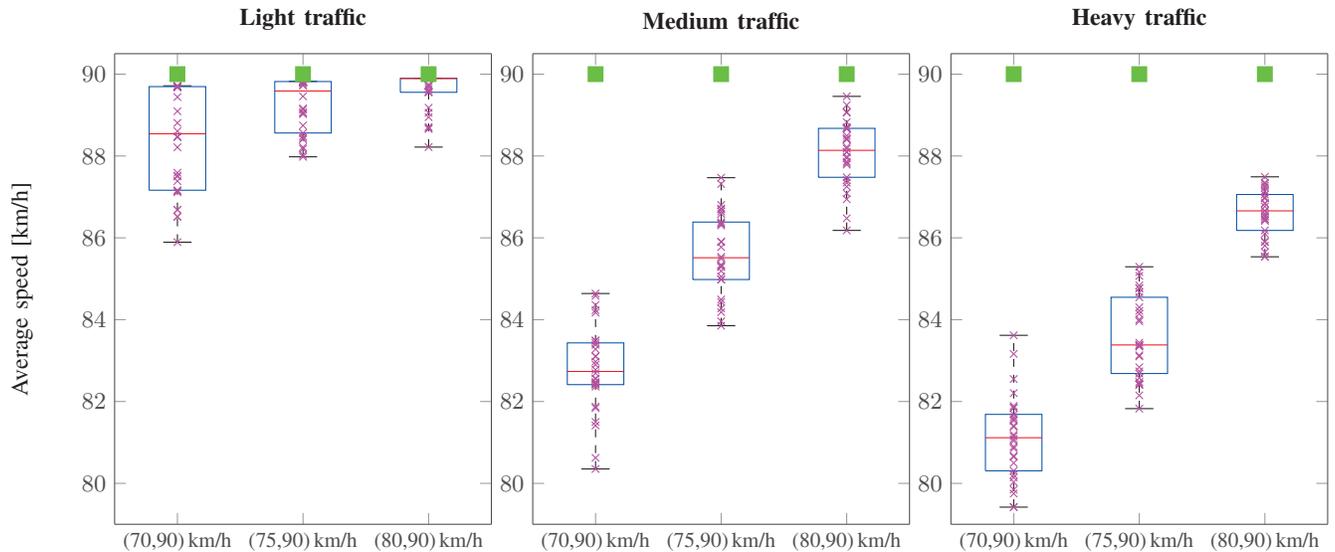


Fig. 9. Box plot of the average speed the trailing HDV had for light (left), medium (middle), and heavy traffic (right). Each individual simulation result are plotted with purple "x". The ideal trailing HDV speed is depicted with a green square. As the traffic density increases, the lower the average speed the trailing HDV could maintain.

then the delayed merging point might not differ that much (in percentage) between different merging maneuvers. For a transport mission, time is a crucial factor followed by fuel savings. Therefore depending on the time limit of the transport, in some situations it might be better only letting the trailing HDV drive faster and catch up instead of the lead

HDV to also slow down, since the merge will be delayed more (in percentage), which might cause the lead HDV to be delayed with its transport. Therefore, a fuel-efficient merging decision will need to be based on the traffic density but also the speed limit of the road (or the speed the cars are driving) in order to correctly merge two HDVs when the fuel savings

from platooning is higher than the additional fuel cost of merging the HDVs in traffic without delaying the transport missions.

V. CONCLUSION

In this paper, we have investigated how a merging maneuver of two HDVs is affected by the surrounding traffic. We simulated for different traffic densities and different merging speeds of the HDVs. For light traffic, the merging point were delayed insignificantly. However, as the traffic density increased, the more the merging point were delayed. The slow down speed of the lead HDV also affected the outcome, the slower the HDV drove the further the merging point got (in percentage). One of the reason is that the cars behind the lead HDV have more difficulty changing lanes due to the big speed discrepancy between the two lanes. In reality, there might be a car who has little incentive to change lanes which might cause some problems with the merging maneuver. Finding possible solutions for this is left as future work. Further investigations need to be conducted on the merging behaviors with lower speed differences between the two lanes (e.g., due to lower speed limit or desired speed of the cars) as well as varying traffic conditions along the road. The concept of forming HDV platoons is to save fuel, therefore a natural continuation is to study how the surrounding traffic and delayed merge affect the total fuel savings compared to the optimal fuel savings with no traffic. Lastly, studies have shown that platooning has positive impacts on the traffic, however, little is known what impact the merging maneuver has on traffic. Investigation on these are left as future work.

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