Effect of the Configuration of Platooning Maneuvers on the Traffic Flow under Mixed Traffic Scenarios

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***Abstract*—Automated driving and platooning are expected to augment the road capacity and improve the traffic. The authors previously demonstrated that it is necessary to take into account platooning maneuvers in order to properly understand and quantify the impact of automated driving on the traffic under mixed traffic scenarios where automated and non-automated vehicles coexist. These scenarios are particularly relevant since platooning and automated driving will be gradually introduced, and non-automated vehicles can interfere with the maneuvers. This study progresses the current state of the art by studying the impact of the configuration of platooning maneuvers on the traffic flow under mixed traffic scenarios. The study focuses on the impact of the desired and safe gaps and the maximum platoon length. These parameters determine if and how platooning maneuvers are executed. The study demonstrates that the three parameters have a significant impact on the traffic flow, and hence their configuration should be carefully studied to maximize the impact of platooning.**

Keywords*— Platooning, maneuvers, autonomous driving, automated driving, simulation, SUMO, Plexe, PERMIT, mixed traffic, traffic flow.

I. INTRODUCTION

Automated driving is expected to have a significant impact on traffic safety and management. First automated driving deployments will rely on technologies such as Cooperative Adaptive Cruise Control (CACC) and platooning. CACC automatically controls the vehicle longitudinal dynamics using radar measurements and information received from other vehicles using V2X communications. Platooning groups vehicles in convoys or platoons where vehicles drive close to each other in order to reduce fuel consumption. The platoons are organized and managed using CACC and V2X communications. Previous studies have shown that platooning can significantly increase the road capacity ([1], [2]). However, these studies were generally conducted with platoons already formed, and hence did not considered the impact that platooning maneuvers would have on the traffic.

Platooning maneuvers require vehicles to accelerate, brake or even change lanes. As a result, maneuvers can require a non-negligible time to be executed, and hence impact the traffic flow. For example, a merge maneuver between two platoons may take more than 15s, while a maneuver for a vehicle to leave the platoon may take more than 7s [3]. The duration of maneuvers will actually increase under mixed traffic scenarios where automated and non-automated vehicles coexist. In fact, non-automated vehicles can interfere automated driving maneuvers. For example, a join or merge maneuver can be interfered whenever a non-automated vehicle is placed in between the automated vehicles participating in the maneuver. Non-automated vehicles can also interfere the leave or split maneuvers that require vehicles to change lanes. Such changes might have to be aborted if obstructed by the presence of non-automated vehicles. The authors took all these aspects into account to demonstrate in [4] for the first time, that platooning maneuvers have a significant impact on the traffic under mixed traffic scenarios where automated and non-automated vehicles coexist. It is important to highlight that the execution of maneuvers is not only influenced by the presence of non-automated vehicles, but also by their configuration. Particularly relevant are the desired and safe gaps or distances. The desired gap is the distance that vehicles driving within a platoon must keep with their front vehicle. The safe gap represents the distance that a vehicle that is changing lane during a platooning maneuver, must maintain with the front vehicle on the other lane and with the vehicle behind (if any). These parameters determine how platooning maneuvers are performed, or even if they can be executed or not. In this context, this study advances the current state of the art by studying for the first time the impact of the configuration of platooning maneuvers on the traffic flow under mixed traffic scenarios. This study is conducted using the simulator PERMIT [5] that can be found in an open-source repository[1]. PERMIT is a simulator that implements platooning maneuvers on SUMO and Plexe.

II. RELATED WORK

Previous studies have analyzed the impact of platooning on the traffic flow, and showed that platooning can increase the road capacity ([1], [2]). According to [2], platooning can increase the road capacity by 20% when 20% of the vehicles in the scenario can form platoons, and the length of the platoons is equal to 6. The study also shows that the road capacity benefits of platooning increase with the penetration rate of the technology and the length of platoons. In fact, Terruzzi et al. showed in [1] that the traffic flow can almost double with an 80% penetration rate of platooning and the possibility for vehicles to form platoons of up to 8 vehicles. The study also

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[1] https://github.com/susomena/PERMIT

shows that platooning can increase the road capacity even if the penetration rate of the technology is low and the length of platoons is small. The study argues that this is due to the lower time headways maintained by the vehicles driving inside a platoon compared to the time headways of ACC (Adaptive Cruise Control) or non-automated driving. These studies were conducted considering that platoons are already formed when introduced in the simulation. As a result, they did not consider the impact of platooning maneuvers on traffic. Such maneuvers can have a significant impact on the traffic as demonstrated by the authors in [4]. The authors showed that the benefits of platooning are overestimated if they are quantified without considering the impact of platooning maneuvers. In particular, the analysis reported in [4] shows that platooning will not improve the traffic until a 20% penetration rate of the technology is reached under mixed traffic scenarios where automated and non-automated vehicles coexist.

The study in [4] was conducted for a fixed configuration of platooning maneuvers, in particular for a fixed value of the desired and safe gaps as well as the maximum length of the platoons. As previously discussed, these parameters are important since they determine how platooning maneuvers are performed, or even if they can be executed or not. The study reported in [3] analyzed the impact of the desired gap on the duration of platooning maneuvers. The study finds out that increasing the desired gap augmented the time needed for vehicles to complete platooning maneuvers. For example, doubling the desired gap almost doubled the time required to perform a merge or split maneuver. It is important noting that [3] did not considered mixed traffic scenarios where automated and non-automated vehicles coexist. Non-automated vehicles can obstruct platooning maneuvers and increase their duration. In fact, the study in [6] showed that non-automated vehicles can delay the formation of platoons by more than 50% under heavy traffic conditions. However, [6] does not analyze the effect that the gaps maintained by automated vehicles may have on this delay. Larger gaps increase the duration of maneuvers. Longer maneuvers are more exposed to possible interference from non-automated vehicles. In this context, this paper advances the current state of the art by studying for the first time the impact of the configuration of platooning maneuvers on the traffic flow under mixed traffic scenarios. In particular, the study focuses on the impact of the desired and safe gaps as well as the maximum platoon length.

III. Discussion on The Impact of the Configuration of Platooning Maneuvers on Traffic

The desired and safe gaps determine how “aggressively or conservatively” automated vehicles execute platooning maneuvers. Larger gaps require more space to execute a maneuver, and hence increase the probability that a non-automated vehicle obstructs the maneuver. Large gaps also increase the duration of the maneuvers, and hence the impact on the traffic as previously discussed. Shorter gaps reduce the probability that non-automated vehicles obstruct automated driving maneuvers, but shorter gaps must be carefully selected so that they do not affect safety. Fig. 1 illustrates an example of how the configuration of the safe and desired gaps can impact platooning maneuvers under mixed traffic scenarios. Fig. 1 shows that when the gaps are short (Fig.1.a), the probability that a non-automated vehicle obstructs a maneuver decreases compared to when the gaps are larger (Fig.1.a). A maneuver is obstructed if a non-automated vehicle does not respect the safe gaps in Fig. 1.

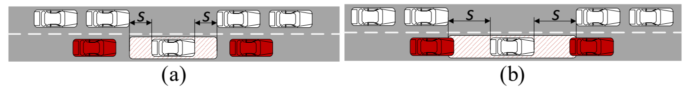

Fig. 1. Impact of the configuration of platooning maneuvers under mixed traffic scenarios. The figure represents a join maneuver. Non-automated vehicles are represented in red. s is the safe gap. (a) No vehicle obstructs the maneuver since s is guaranteed. (b) The maneuver is obstructed since two vehicles are at a distance shorter than s to the vehicle that must change lane.

Another parameter that also affects platooning maneuvers and their impact on traffic is the maximum platoon length. This length represents the maximum number of vehicles that can drive inside a platoon. This parameter affects maneuvers, for example, when an automated vehicle wants to join an existing platoon or two platoons want to merge. In the first case, a vehicle will not be allowed to join a platoon if the platoon has already reached its maximum length. Two platoons are also not allowed to merge (even if none of them have reached their maximum length) if the sum of their lengths exceeds the maximum platoon length. This can limit the benefit of platooning since its impact on the road capacity depends on the length of the platoons [2]. On the other hand, it is also important to take into account that maneuvers involving large platoons require more time to be executed and also more space. As previously discussed, this increases the probability that non-automated vehicles obstruct the maneuvers.

IV. Simulation Setup

This study has been conducted using the platooning simulator PERMIT [5]. PERMIT is based on the microscopic traffic simulator SUMO [7] and its platooning extension Plexe [8]. PERMIT extends Plexe by introducing the capability to simulate the join, merge, leave and split automated driving maneuvers in mixed traffic scenarios. More details on PERMIT and the implementation of these maneuvers can be found in [5].

Following [1], this study simulates a 10km ring road scenario with a traffic density of 36veh/km. The road has two lanes, and ten road edges. Vehicles can choose any edge as source or destination of their route. The routes of all vehicles are randomized. The percentage of automated vehicles in the scenario varies from 0% to 100%. The mobility of conventional or non-automated vehicles is modeled using the Krauss [9] car-following and LC2013 [10] lane-changing models. These models control the vehicles’ longitudinal and lateral dynamics respectively. The Krauss model has been set up with a time headway of 1s. The LC2013 lane-changing model is also used to control the lateral dynamics of automated vehicles. Depending on the role and context of automated vehicles, different models are used to model their longitudinal dynamics. Platoon leaders and automated vehicles driving outside a platoon use the ACC model implemented in Plexe. This ACC model is described in [11], and has been here configured with a time headway of 1.4s following [1].

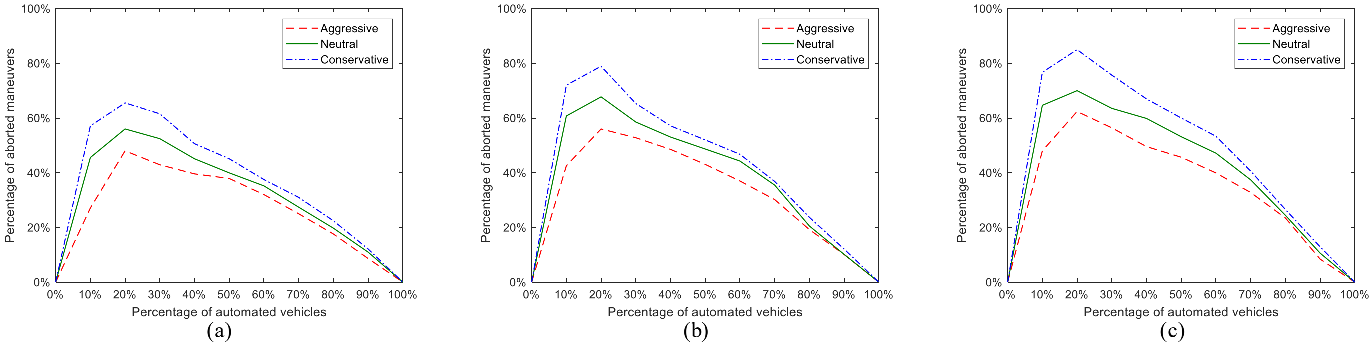

Fig. 2. Percentage of aborted platooning maneuvers as a function of the percentage of automated vehicles in the scenario for a maximum platoon length of (a) 2 vehicles, (b) 4 vehicles, and (c) 8 vehicles.

Automated vehicles driving inside a platoon, and following the platoon leader, use the California PATH CACC model implemented in Plexe. This model is described in [11]. We have configured the CACC model to maintain three different desired gaps with the front vehicle: 1m, 5m and 10m. We refer to these three configurations as aggressive, neutral and conservative, and their values have been chosen following [12], [1] and [13], respectively. The three configurations have been proven to be string stable, and no collisions occur when the platoon leader makes an emergency braking of $5m/s^2$. It is then important to emphasize that the three configurations considered allow a safe driving, even the "aggressive" one. The safe gap used during the platooning maneuvers has been set equal to 1.25 times the desired gap. The aggressive, neutral and conservative configurations therefore utilize safe gaps equal to 1.25m, 6.25m and 12.5m, respectively. Simulations have been conducted for maximum platoon lengths equal to 2, 4, 6 and 8 vehicles. Larger values have not been considered since [1] showed that they do not significantly benefit the road capacity.

V. RESULTS

Fig. 2 represents the percentage of aborted maneuvers as a function of the percentage of automated vehicles in the scenario. The results are represented for the three configurations of the desired and safe gaps, and maximum platoon lengths of 2, 4 and 8 vehicles[2]. Fig. 2 shows that the percentage of aborted maneuvers initially increases with the percentage of automated vehicles and then decreases. When the percentage of automated vehicles in the scenario is low, automated vehicles find many obstacles (i.e. non-automated vehicles) during their maneuvers and have to abort them. As the percentage of automated vehicles increases, the total number of maneuvers also increases, and so does the abortion rate. This trend is maintained until the percentage of automated vehicles in the scenario exceeds 20%. From this point onwards, platooning maneuvers are eased by the larger presence of automated vehicles, and hence the lower probability of finding an obstacle during maneuvers. Fig. 2 also shows that the percentage of aborted maneuvers increases with the maximum platoon length. The total number of platooning maneuvers in the scenario increases with larger values of the possible maximum length of platoons. This is the case because automated vehicles seek to join or merge platoons so that their length increases. However, larger lengths also augment the duration of the maneuvers. This increases the probability of finding an obstacle during the maneuvers and the rate of aborted maneuvers (especially for low percentages of automated vehicles in the scenario).

Fig. 2 also shows that the configuration of the desired and safe gaps has a relevant impact on the success (or not) of platooning maneuvers. In particular, the figure shows that shorter gaps reduce the percentage of aborted maneuvers. Shorter gaps require less time and space for maneuvering. It is hence less probable to find obstacles (non-automated vehicles) during the maneuvers that would require aborting them. The difference between the different configurations of the desired and safe gaps is larger when the probability of finding obstacles during the maneuvers is more significant. This explains why the differences reduce in Fig. 2 as the percentage of automated vehicles in the scenario increases.

The trends observed in Fig. 2 have a direct impact on the traffic flow as shown in Fig. 3. This figure represents the traffic flow in the scenario as a function of the percentage of automated vehicles. The results are again represented for the three configurations of the desired and safe gaps, and maximum platoon lengths of 2, 4 and 8 vehicles. Fig. 2 showed that shorter desired and safe gaps reduce the percentage of aborted maneuvers. Reducing the percentage of aborted maneuvers increases the length of platoons, which has a positive impact on the traffic flow as shown in Fig. 3. This is due to the fact that automated vehicles driving inside a platoon maintain a shorter distance with their front vehicles than non-automated vehicles. This allows other vehicles to drive faster, and augments the traffic flow and the road capacity. The positive impact of shorter gaps in the traffic flow is maintained as the percentage of automated vehicles in the scenario and the maximum platoon length augment (Fig. 3). It is interesting to note that large desired and safe gaps significantly reduce the positive impact of platooning on the traffic flow. In fact, Fig. 3a (maximum platoon length of 2 vehicles) shows that the conservative configuration of gaps results in that the traffic flow only increases by 9.39% when 100% of the vehicles in the scenario are automated compared to the case in which there are no automated vehicles. The increase observed with the neutral and aggressive configurations is equal to 26.09% and 39.21%, respectively. Fig. 2 showed that augmenting the maximum platoon length increases the percentage of aborted maneuvers.

[2] The same trends have been observed for a maximum length of 6 vehicles.

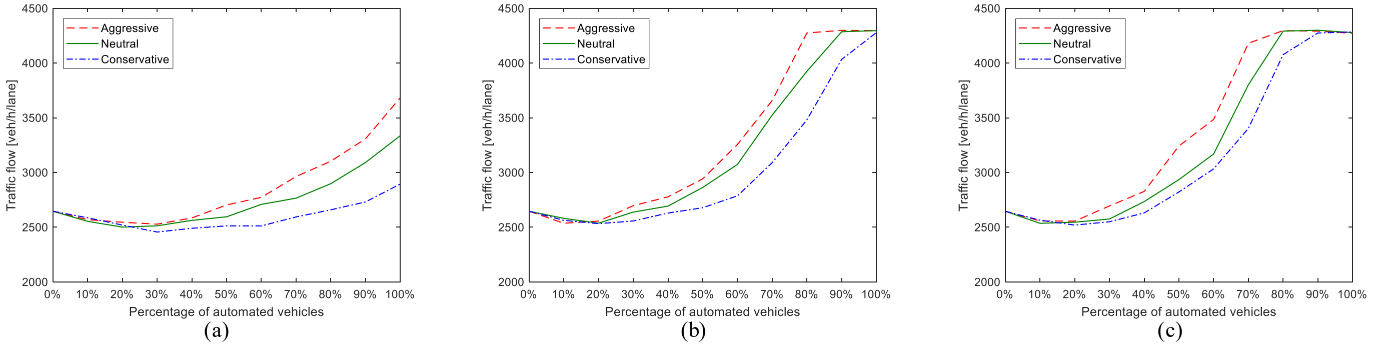

Fig. 3. Traffic flow as a function of the percentage of automated vehicles in the scenario for a maximum platoon length of (a) 2 vehicles, (b) 4 vehicles, and (c) 8 vehicles.

Despite this effect, Fig. 3 shows that increasing the maximum length augments the traffic flow, in particular when the percentage of automated vehicles in the scenario is higher than 20%. This is due to the formation of larger platoons that reduce the distance between vehicles inside the platoons, and hence augments the road capacity and the traffic flow. Fig. 3 shows that this positive aspect of larger platoons compensates the larger percentage of aborted maneuvers observed in Fig. 2. Fig. 3 also shows that the traffic flow saturates for a maximum platoon length of 4 and 8 vehicles (and also for a length equal to 6 vehicles). This is due to the fact that for a constant traffic density, the traffic flow only increases if the traffic speed increases. Once this maximum speed is reached, the traffic flow cannot further increase. This is actually what happens when the traffic flow saturates. It is interesting to observe in Fig. 3 that shorter gaps (aggressive configuration) result in that the maximum permitted speed is reached for lower percentages of automated vehicles in the scenario than with the neutral or conservative configurations.

Fig. 3 clearly shows the positive impact of platooning on the traffic flow. This positive impact generally increases with the percentage of automated vehicles in the scenario. However, it is important noting that Fig. 3 presents a different trend to that observed in [2]. This study indicated that the traffic flow increases with platooning, even when there is a low percentage of automated vehicles in the scenario. Fig. 3 actually shows that such low percentages slightly degrade the traffic flow. The flow starts improving when the percentage of automated vehicles in the scenario is higher than 20%. This difference with [2] is due to the fact that [2] did not model platooning maneuvers, and hence did not consider their impact. As shown in Fig. 2, the percentage of aborted maneuvers increases when the percentage of automated vehicles in the scenario is low. This is due to the high probability that non-automated vehicles obstruct the maneuvers. The percentage of aborted maneuvers starts decreasing when the percentage of automated vehicles in the scenario exceeds 20%.

VI. Conclusions

This paper has studied the impact of platooning maneuvers on the traffic flow, and the effect of their configuration under mixed traffic scenarios. In particular, this paper has studied the effect of the desired and safe gaps, and the maximum platoon length. The study has demonstrated that these parameters have a significant impact on the traffic flow under mixed traffic scenarios since they determine if platooning maneuvers can be executed, and how they are performed. The configuration of these parameters should hence be carefully studied in order to maximize the impact of platooning. These findings complement those reported in [4], where the authors demonstrated that it is necessary to take into account maneuvers when analyzing the impact of platooning and automated driving on the traffic.

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