The Impact of Flexible Platoon Formation Operations

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Abstract—Vehicle platooning, a coordinated vehicle movement strategy, has been proposed to address a range of current transport challenges such as traffic congestion, road safety, energy consumption and pollution. While the current literature mainly focuses on platoon control strategies and intra-platoon communication, comparatively little work is done on how to form these platoons. Literature assumes platoon formation by tail merge which is sufficient only for planned formation on a ramp or at a ramp-highway junction. In this paper we study the impact of three different merge operations, namely front, middle, and tail merge. The efficiency of these operations is analyzed under different scenarios, varying the vehicles speed adjustment strategy, traffic density, and the density of mergeable vehicles. The impact of the merge operations is represented in terms of merge time, merge distance, average traffic speed, and merge success rate. Our experiments show that in an ideal *no traffic* scenario, the middle merge is costlier in terms of merge time for the same merge distance whereas in the presence of traffic middle merge helps in quick platoon formation on an average in a higher traffic density in particular. This insight should provide a more flexible toolkit for planning a platoon formation.

Index Terms—Vehicle platooning, platoon formation, platoon-impact, platooning strategy.

I. INTRODUCTION

VEHICLE platooning refers to a closely coordinated vehicle following mechanism without having any mechanical linkage while maintaining a safe distance. Platooning has been proposed with the primary objectives of cutting down fuel consumption [1], and increasing road capacity and throughput [2]. Platooning also targets road safety as the coordinated vehicle behavior minimizes the chance of collision [3].

On-road platooning trials [4]–[11] have demonstrated vehicle-following mechanisms and platoon operations such as merge and split. In most of these cases, platoons are tested in a controlled environment where only a limited number of platoon operations are performed. Also, the formation was a planned process and performed on a ramp or at a ramp-highway junction. In this paper, however, we consider platoons, traveling in traffic and being allowed to form in an opportunistic manner. In this case, a more flexible choice of merging operations, such as front merge, middle merge, and tail merge is possible. We will study their impact on traffic, and the impact of traffic on these merge operations. For example,

an ongoing platoon merge operation may impede the rest of the traffic. Also, dense traffic may disrupt an ongoing merge operation, such as a tail merge being disrupted by a vehicle moving in between. Therefore, it is important to investigate the impact of traffic on platoon formation operations, and the impact of platoon formation operations on traffic. Understanding the impact of choosing a merge operation should provide a more flexible toolkit for planning a platoon formation. Such investigations are not suited for on-road trials in the presence of the real traffic. Hence, our investigation is simulation-based.

In the academic literature, vehicle platoon formation *operations* are rarely analyzed. What has been studied are platoon formation *strategies* such as *destination grouping*, *dynamic grouping*, *dynamic grouping and platoon splitting*, *random assignment*, *optimized platoon formation*, and *transient platoon formation* are proposed [2], [12], [13] to maximize the platooning benefit in terms of highway throughput, lane capacity, trip time, average platoon length, platoon ratio, platoon stability, and the average waiting time for platoon formation. These strategies follow two principles: to form platoons of reasonable length with 10-20 vehicles, and to form platoons that stay intact for longer times. Hence, these formation strategies group the vehicles based on their destinations. Yet all these strategies are limited to a platoon formation at highway ramps, or a vehicle on the ramp merging with a vehicle or a platoon traveling along the highway. For these strategies tail merge is sufficient. Besides, the evaluation of these strategies has generally not considered feedback on traffic flow.

We will address this gap in the analysis of the impact of platoon formation operations on traffic, and vice-versa of traffic on the platoon formation operations. Among the three merge operations, in principle, the middle merge comprises of one split and two tail merge operations [14], and thus is expected costlier in terms of operation execution time than front or tail merge. However, in dense traffic, the middle merge may be cheaper or even the only option, depending on the position of the requesting vehicle with respect to the platoon. Middle merge could be the only option when lanes merge. Other constraints can enforce or favor a front merge. Depending on the requesting vehicle's position and the traffic, the operation execution times could vary significantly. Thus, platoon merging operations should be chosen flexibly considering these two parameters.

Accordingly, this paper aims to address the following research challenges:

- 1) *Behavior of front, middle and tail merge.* The paper implements all three merge operations in a simulation environment. We focus on a single vehicle and a single

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platoon in our first experiment. The goal is to observe the operation execution time for the three different merge operations, in scenarios with the speed adjustments of platoon members, the speed adjustment of the merging vehicle, the merging vehicle at higher speed and the other scenario with the platoon at higher speed.

- 2) *Impact of traffic on merge operations.* Once all the merge operations are analyzed without traffic, the next step is to investigate the impact of traffic on merge operations. In this case, the merging vehicle speed, platoon speed, and merge operations need to be adjusted based on the surrounding traffic. Traffic may result in longer execution times of merge operations, and require a flexible choice of merging operations.
- 3) *Impact of merge operations on traffic.* The impact of merge operations on the traffic is also analyzed in terms of average traffic speed during the operations.

Analyzing these challenges, the key contributions of this work are:

- 1) Implementation of different platoon merge operations and scenarios in a simulation platform.
- 2) Analysis of platoon merging operations in the presence of traffic, where the mutual impact is observed in properties such as total operation time, total travel distance, average traffic speed and the operation success rate.

The hypothesis for this research is that a flexible choice of merge operations, depending on the position of the vehicle and the surrounding traffic, is beneficial from operation execution time and average traffic speed perspective. The support for this hypothesis would suggest guidelines for the choice of an operation in a given situation.

The paper provides a brief review of platoon simulations related to platoon formation strategies, presented in Section II. Section III describes the basic blocks of our proposed simulation, and Section IV demonstrates the experiments. An analysis of the experimental results and the key insights are presented in Section V. Section VI concludes the paper.

II. LITERATURE REVIEW

In the literature, different types of platoon formation strategies have been proposed and tested in simulation environments. These formation strategies can be classified as ramp-based formation and ramp-highway-based formation. In ramp-based formations [12], the formation of the platoon takes place at the ramp. Vehicles are queued up at the ramp lanes in a per-lane queuing strategy. They wait for the predetermined termination conditions such as waiting time-out, reaching of maximum platoon length, or need to create space for newly arrived vehicles. There are four types of ramp-based formation strategies proposed by Hall and Chin [12]:

- 1) *Destination grouping:* In this strategy, the lanes of the entrance ramp are preassigned for a destination range.
- 2) *Dynamic grouping:* In dynamic grouping, a destination range is pre-decided. A platoon is created with the constraint that the difference between the nearest and farthest destination of platoon members is less or equal to the defined destination range.

- 3) *Dynamic grouping and platoon splitting:* In this strategy, a platoon is formed with the constraint that platoon members are ordered based on their destination. It implies the platoon leader has the farthest destination and the last member has the nearest destination.

- 4) *Random formation:* As the name suggests, in this strategy the vehicles are assigned to the lanes randomly and the platoons are generated in an ad-hoc manner.

The other type of formation strategy is ramp-highway-based platoon formation:

- 1) *Optimized platoon formation:* This strategy relies on the optimization of vehicle assignment based on their destination [2]. The logical assignment of a vehicle is done on the ramp whereas the physical assignment takes place on the highway.
- 2) *Transient platoon formation:* In transient platoon formation [13], a temporary assignment of a vehicle to a non-feasible platoon is allowed in absence of a feasible platoon.

Among these strategies, ramp-based formation strategies demand extra time at the ramp for platoon formation. The dynamic grouping and platoon splitting strategy ensures platoon stability while compromising platoon average length and fuel efficiency. Similarly, the transient platoon formation strategy enhances the platoon ratio while compromising platoon stability. In all these strategies, only tail merge is required. Whereas, in realistic traffic, a vehicle can express a merge request when approaching the platoon on the highway from the back, front or the side of the platoon. As the above mentioned formations take place at ramp or ramp-highway junction, the formation impact on traffic or the impact of formation on traffic cannot be realized in the above cases.

Apart from the mentioned platoon simulations, Amoozadeh et al. proposed a platoon management protocol and simulated three platooning scenarios: leaving of the leader, leaving of a follower, and entry at the end [15]. This work analyzed a platoon's speed profile, duration of operation and throughput with respect to platoon size and inter-platoon spacing in the absence of traffic.

Platoon formation strategies have been mainly evaluated in the VISSIM simulation platform [16]. Platooning of autonomous vehicles has also been tested in the SUMO simulation platform [17]. Amoozadeh et al. tested the platooning scenarios in the integrated simulation platform VENTOS.

III. MODEL DESCRIPTION

Any traffic flow can be modeled in at least three ways [18]. In macroscopic models, traffic flow is characterized by the aggregated macroscopic variables of density, volume, and speed. In microscopic models, the motion of each vehicle composes the traffic stream. This implies modeling the actions, e.g., acceleration, deceleration, and lane change, of each vehicle in response to the surrounding traffic. The mesoscopic models capture the essentials of movement dynamics and are computationally more efficient than microscopic models. In this research, however, a microscopic approach is taken to model traffic flow since we aim to observe and model the microscopic parameters such as the speed, relative position of the merging vehicle to the platoon.

A. Car-Following Model

Since our research uses the microscopic approach, a car-following model is required to control the longitudinal movement. A common practice is to assume the movement of a vehicle is typically governed by its predecessor. While this assumption is true for any free flow vehicle of the traffic, however, simulating a platoon is different from simulating the free flow vehicles. The key difference is to keep a constant distance for the platooning vehicles which is not necessary for free flow vehicles' movement. In the case of free flow vehicles, the distance between the two vehicles may change. Thus, two types of car-following models are used in this research.

The platoon leader and all other free flow vehicles adopt the Intelligent Driver Model (IDM) [19]. In IDM, the preceding vehicle influences the following vehicle's speed. As the following platoon members need to keep a fixed headway instead of maintaining the desired speed, they adopt the platoon leader's speed. An exception may happen during platoon maneuvers, such as a middle merge operation, when one or more members can obtain different speeds. In general, any change in platoon leader's speed results in instant speed change for all platoon followers without any delay. Micro-effects such as communication delay or disturbances are neglected here. Despite simplifications, these two car-following models are suited to analyze the scenarios under consideration.

B. Lane Change Model

Along with the longitudinal control, lane change model is needed for vehicle's lateral control on multi-lane roads. In general, a free flow vehicle performs a lane change when the lane is congested or blocked, or multiple lanes merge to a lesser number of lanes. A platoon follows the same principal for lane change as the free flow vehicles follow. Additionally, the platoon leader checks if the lane change is feasible for the entire platoon while performing the lane change. Only if it is safe to move the entire platoon to the next lane without causing any crash, the platoon leader decides for the lane change. Once decided, the entire platoon moves to the next lane in the next simulation step. This research uses the default lane change model of SUMO, LC2013 [20] both for free flow vehicles and platoon. Lane change may also be required during a merge operation, if the merging vehicle is not in the same lane with the platoon. In these cases, the merging vehicle changes its lane after confirming the feasibility and safety of doing it.

C. Proposed Platooning Model

This research aims to analyze a platoon's behavior in the presence of traffic, specifically, the impact of vehicle platooning on traffic and the impact of traffic on the vehicle platooning. To fulfill the research goal, a platoon simulation model is developed. In the simulation model, suitable merging vehicles are selected from the traffic. We assume more than one vehicle could express the merge request to an existing platoon and the platoon leader selects a favourable one. While selecting the merging vehicle, we only consider platoonable vehicles. Point to note, this research considers only a percentage of the traffic is platoonable. The selected vehicles merge

with a platoon one after another until the platoon reaches its maximum size. Three merging strategies front merge, middle merge, and tail merge are evaluated using this simulation model. The merge completion time, distance covered by the platoon, merge success rate, and average traffic speed during the merge operations are computed for analysis.

The simulation model is presented in Algorithm 1. The variables and the parameters are used in the algorithm have following meaning.

- P is the platoon consist of number of vehicles
- T is the traffic consist of platoonable and non-platoonable free flow vehicles
- RS is the results computed from the simulation
- $nVeh$ is the suitable merging vehicle
- $lenP$ is the size of the platoon in terms of vehicles
- $spdP$ is the speed in next iteration, a platoon obtains to complete the operation without causing any collision
- $spdV$ is the speed in next iteration, the merging vehicle obtains to complete the operation without causing any collision
- N is the simulation network
- R is the route of the vehicles
- p_{is} is the initial platoon size in terms of vehicles
- p_{ms} is the maximum vehicles a platoon can accommodate
- p_0 is the desired platoon speed
- v_0 is the free flow vehicle speed
- b_{len} is the predefined buffer range with respect to the platoon used to select a suitable merging vehicle
- h is the intra-platoon gap
- o_{dis} is the out of reach distance
- t_{out} is the operation time out

Step 1: at first a platoon of size p_{is} is initialized in the given network N , with a route R , and platoon's speed p_0 (line 2).

Step 2: other free flow vehicles are also initialized, termed as traffic with speed v_0 (line 3).

Step 3: maneuver state indicates if a platoon is performing any operation or not. Initially, the platoon is not in a maneuver state, $isManeuverState$ is set as false. Platoon size $lenP$ is initialized with p_{is} . The merging vehicle $nVeh$ is not selected yet, so it is initialized with the null value (line 4-6).

Step 4: next, the model checks if the platoon reaches its maximum length or not. If the platoon reaches its maximum size limit, the simulation ends (line 7).

Step 5: if the platoon can still accommodate vehicles to merge, and the platoon is not in maneuver state already, then the next task is to find out a suitable mergeable vehicle $nVeh$ from the traffic to initiate the merge operation (line 8-13). The suitable mergeable vehicle is selected within a buffer range b_{len} with respect to the platoon. The details of the selection procedure are given in the following paragraph.

Step 6: the merge operation is initiated with that identified vehicle $nVeh$. In the maneuver state, the platoon speed and the vehicle speed are adjusted to obtain the required intra-platoon gap h and to perform the merge operation (line 27-29).

Step 7: if the merge operation takes longer than a particular limit t_{out} , the operation is canceled and the model searches for a new suitable vehicle for merge. This research considers time out value as 180 s, which is nearly three times greater than average merge time. The merge operation is also canceled if the merging vehicles move far apart, out of range o_{dis} , impeded by the traffic. Here, o_{dis} value is considered as 2km which is one-fourth of the network length (line 15-19).

Algorithm 1: Platooning Model

Input: network N , route R , parameters $p_{is}, p_0, v_0, p_{ms}, b_{len}, t_{out}, o_{dis}, h$
Output: results RS

```

1 begin
2    $P \leftarrow \text{InitializePlatoon}(N, R, p_{is}, p_0)$ 
3    $T \leftarrow \text{InitializeTraffic}(N, R, v_0)$ 
4    $\text{isManeuverState}(P) = \text{false}$ 
5    $\text{len}P = p_{is}$ 
6    $nVeh = \text{null}$ 
7   while  $\text{len}P < p_{ms}$  do
8     if  $\text{isManeuverState}(P)$  then
9       if  $\text{isEmpty}(nVeh)$  then
10         $nVeh \leftarrow \text{FindMergingVehicle}(P, T, b_{len})$ 
11         $\text{isManeuverState}(P) = \text{true}$ 
12      endif
13    endif
14    else
15      if  $\text{isOperationTimeOut}(P, nVeh, t_{out})$  OR
16       $\text{isOutOfRange}(P, nVeh, o_{dis})$  then
17         $\text{isManeuverState}(P) = \text{false}$ 
18         $nVeh = \text{null}$ 
19      endif
20      if  $\text{isMerged}(P, nVeh)$  then
21         $\text{SetDesiredSpeed}(P, p_0)$ 
22         $\text{isManeuverState}(P) = \text{false}$ 
23         $nVeh = \text{null}$ 
24         $\text{len}P = \text{size}(P)$ 
25      endif
26      else
27         $\text{spd}P \leftarrow \text{SetNextIterationSpd}(P)$ 
28         $\text{spd}V \leftarrow \text{SetNextIterationSpd}(nVeh)$ 
29         $P \leftarrow \text{Merge}(P, nVeh, \text{spd}P, \text{spd}V, h)$ 
30      endif
31    endif
32  end
33   $RS \leftarrow \text{Results}(\text{merge time, merge distance, merge success rate, average traffic speed})$ 
34 end

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Step 8: once a merge operation is completed (line 20-25), the next suitable merging vehicle is identified to perform next merge operation. The simulation runs until all the merge operations are completed. Finally, the operation execution time, total travel distance, merge success rate, and the average speed of the traffic during the merge operation is recorded to compare different merging strategies.

The selection of a suitable mergeable vehicle is an important part of the proposed platooning model. Typically, a merging vehicle can be selected randomly from the traffic. But, it may results in longer execution time, if the selected vehicle is far apart from the platoon, or the selected vehicle is surrounded by dense traffic, or the speed difference between the platoon and the selected vehicle is high. Also, selection of an improper candidate may lead to failure of the merge operation. As we evaluate different merging strategies in terms of merge completion time and merge success rate, it is important to select a merging vehicle that ensures merge success and likely to complete the operation in lesser time. Ideally, a suitable merging vehicle needs to be chosen based on three parameters: distance between the platoon and the vehicle, surrounding traffic of the vehicle, and the speed difference between the

platoon and the vehicle.

Figure 1 represents a traffic scenario of front merge where, a suitable merging vehicle needs to be selected. In this figure,

Fig. 1. Merging candidate selection

the platoon P consists of three vehicles, one platoon leader V_{pl} and two platoon followers V_{pf} . The traffic is consist of platoonable free flow vehicles V_m and non-platoonable free flow vehicles V_{nm} . Now, for front merge only one position is available for the merge, that is at the front of the platoon. Therefore, the suitable merging vehicle is likely to be one of the two vehicles, the predecessor platoonable vehicle $nfVeh$ and the successor platoonable vehicle $nbVeh$. The distance between the predecessor platoonable vehicle and the merge position is denoted by $disFV$. $disBV$ denotes the distance between the successor platoonable vehicle and the merge position. Similar to the front merge, for tail merge also only one merge position is available: at the back of the platoon. Therefore, the merging vehicle can be chosen in a similar way. The following section describes the mergeable vehicle selection processes based on the merging strategies.

1) *Merging vehicle selection - front and tail merge:* As mentioned before, the suitability of merging vehicle depends on the three key parameters: distance between the platoon and the vehicle, surrounding traffic of the vehicle, and the relative speed of the platoon and the vehicle. Using these parameters, we propose a heuristic that identifies the most suitable merging vehicle from the traffic. The details of the selection process are shown in Fig. 2. The variables and the parameters are used in the flowchart have the following meaning:

- $nfVeh$ is the nearest predecessor platoonable vehicle
- $nbVeh$ is the nearest successor platoonable vehicle
- $nVeh$ is the selected merging vehicle
- $disFV$ is the distance between $nfVeh$ and merge position
- $disBV$ is the distance between $nbVeh$ and merge position
- $spdBV$ is the speed of $nbVeh$
- $spdP$ is the speed in next iteration, a platoon obtains to complete the operation without causing any collision
- $cDis$ is the comparative distance score
- $traD$ is the surrounding traffic
- $wgtS$ is the weight based on comparative speed $spdBV$ and $spdP$
- $wgtT$ is the weight based on $traD$
- T is the threshold to select $nbVeh$

Step 1: each platoon is associated with a buffer area containing some platoonable vehicles V_m and some non-platoonable vehicles V_{nm} . The platoonable vehicles within the buffer area considered as candidates for platoon merge operation. In Figure 1, three candidate vehicles are shown. Among the candidate vehicles, the nearest predecessor vehicle $nfVeh$ and the nearest successor vehicle $nbVeh$ are identified. These two vehicles are more suitable for the merge as they

Fig. 2. Merging vehicle selection - front and tail merge

are closest to the merge position. *nfVeh* and *nbVeh* are not necessarily in the same lane with the platoon. Their positions are computed relative to the merging position.

Step 2: if no mergeable vehicle is available within the buffer area, the search for a suitable merging vehicle terminates.

Step 3: if only one vehicle either *nfVeh* or *nbVeh* is in the buffer area, then that is considered as the merging vehicle.

Step 4: if there are two candidate vehicles, *nfVeh* and *nbVeh*, we compare the distance *disFV* and *disBV* of these two vehicles from the merge position. We saw that if *nfVeh* has a shorter merging distance, it can slow down and merge with platoon most of the time, if the platoon's speed is not impeded. Whereas, if *nbVeh* has a shorter merging distance, it may or may not be able to merge to the platoon due to the surrounding traffic and speed difference. If *disFV* is shorter than *disBV*, then *nfVeh* is selected as merging vehicle.

Step 5: if *disBV* is shorter than *disFV*, then the more suitable candidate is decided based on a heuristic score. The heuristic considers the comparative distance score *cDis*, the surrounding traffic *traD*, and the speed of *nbVeh* vehicle *spdBV*, and speed of the platoon *spdP*.

Step 6: the comparative distance score *cDis* is calculated as shown in Eq. 1.

$$cDis = \frac{\log(disFV - disBV)}{\log(disFV + disBV)} \quad (1)$$

The value of *cDis* indicates if *nbVeh* is preferable for merge based on the distance. Instead of using raw distance values we have used *log* to scale down the comparative distance score between 0 to 1. We have considered few scenarios where *nfVeh* and *nbVeh* are i) close to the platoon (e.g. 40 m, 30 m, *cDis* is 0.54) ii) *nfVeh* is far from platoon (e.g. 250 m, 50 m, *cDis* is 0.93) iii) both are far from platoon (e.g. 250 m, 240 m, *cDis* is 0.37) to validate the *cDis* calculation. When *nfVeh* and *nbVeh*

are comparatively far from the merge position, *cDis* penalizes the *nbVeh*. Here, we assume for long distance, speeding up will be difficult for *disBV* to reach the merge position in presence of traffic. Comparatively, it will be easier for *disFV* to slowdown to reach the merge position.

Step 7: the other key parameter is the relative speed of *nbVeh* and platoon. If the speed of *spdBV* is not hindered by its predecessor (Figure 1 vehicle V_{nm}) and *spdBV* is higher than *spdP*, a weight *wgtS* is added to calculate the heuristic score. Otherwise, *wgtS* is subtracted in the calculation. This parameter indicates if *nbVeh* is preferable for merge, based on the current speed. We have run several merge testcases to calibrate and decide the value of *wgtS* and set it as 0.2.

Step 8: the surrounding traffic *traD* is computed based on the total number of vehicles between *nbVeh* and the merging position. In Figure 1 shaded region we can see there are two vehicles in between *nbVeh* and the merging position, one in the same lane of *nbVeh* and the other is in the lane of the platoon. In order to minimize the disruption in merge operation, we aim not to have more than two vehicles in the same lane and more than five vehicles in all lanes¹. If this can not be achieved, we apply a penalty by subtracting a weight *wgtT* from the heuristic. After running several testcases, *wgtT* is set to 0.2.

Step 9: finally, we compute the heuristic score using Eq. 2.

$$\begin{aligned}
 score &= cDis + wgtS + wgtT, & \text{for } spdBV > spdP & \text{and no congestion} \\
 &= cDis + wgtS - wgtT, & \text{for } spdBV > spdP & \text{and congestion} \\
 &= cDis - wgtS + wgtT, & \text{for } spdBV \leq spdP & \text{and no congestion} \\
 &= cDis - wgtS - wgtT, & \text{for } spdBV \leq spdP & \text{and congestion}
 \end{aligned} \quad (2)$$

If the heuristic score is greater than a threshold *T* (0.6), *nbVeh* is selected as the merging vehicle.

2) **Merging vehicle selection - middle merge:** In the case of front merge and tail merge only one merge position is available. But for the middle merge, in general, more than one merge position is available: exactly $n - 1$ positions if n is the length of the platoon. Hence, a variable number of platoonaable vehicles near to the platoon can be selected in an initial screening. Again, for each of these candidate vehicles, all $n - 1$ middle merge positions are available. An experiment is conducted to determine the most suitable middle merge position, which is described in the next section. From all the candidate vehicles, the most suitable one for the merge is selected similarly to the previous merging vehicle selection process. Here also the decision has been taken based on the three parameters - the distance between the vehicle and the merge position, surrounding traffic of the vehicle, and the speed difference between the platoon and the vehicle.

The developed model is used to analyze the three different platoon merging operations performed in absence as well as in the presence of traffic. The details of the analysis are presented in the next section.

¹The values are decided based on merge success rate and the merge duration after running several test cases in our experimental setup. These values can be changed of course depending on the typical traffic density in the countryside.

IV. EXPERIMENT

This section presents a detailed description of experiments and the results observed.

A. Environment Setup

All experiments are carried out in the open source traffic simulator SUMO (Simulation of Urban MObility) [21], [22]. MATLAB [23] is used to control the vehicles externally. More specifically, vehicles' speed is controlled by MATLAB during the platoon maneuver. Here, TraCI (Traffic Control Interface) [24] works as the interface between MATLAB and SUMO. Interaction happens based on a client-server protocol where MATLAB acts as the client, and SUMO as the server.

B. Simulation Setup

To simulate the platoon and vehicles and to evaluate different merge operations, a circular traffic network is designed. The network consists of eight segments. The length of each segment is around 1km, forming a ring of total 8km. Half of the highway has three lanes, and the other half has four lanes. All of the previous literature has considered straight highways with intersections to evaluate platoon formation strategies. The circular network chosen here to compel the vehicles to move in a loop, such that vehicles cannot leave the simulation after some time, and the full impact of merge operations can be observed over any time frame. Furthermore, the combination of three and four lane highway segments forces the vehicles to merge lanes at some points and to spread out across lanes, providing a degree of disturbance in the traffic. In this simulation, we have allowed overtaking of vehicles in all lanes not only in the outer lanes. We have realized the smooth flow of traffic without a traffic shock during different merge operations as there are free available lanes and the vehicles can perform lane change and overtake. However, for the testing purposes we have also experimented with one-two and two-three lane networks. In those scenarios, we have noticed the shock effect in traffic.

The parameters and their values used in the simulation are listed in Table I.

C. Performance Metrics

In this research four metrics are used, namely, merge time, merge distance, average traffic speed, and merge success rate.

- 1) *Merge time*: Merge time is computed as the time duration between the merge operation initiated and the merge operation completed. Merge time is important because longer merging times may slow down the rest of the traffic. Naturally, a shorter merging time is desirable. Also, in some experiments, a number of consecutive merge operations are performed. In these cases, a metric Merge Completion Time (MCT) is calculated as the sum of all merge times.
- 2) *Merge distance*: Merge distance is the distance required to complete the merge operation. In the experiments where a number of consecutive merge operations are performed a metric Total Travel Distance (TTD) is calculated as the

TABLE I
PARAMETERS USED IN PLATOON SIMULATION

Parameter	Description	Value
s_0	Minimum gap at stand-still	2 m
t	Safe time headway	1 s
a	Maximum acceleration	3 m/s ²
b	Maximum deceleration	3 m/s ²
δ	Acceleration component	4.0
l	Vehicle length	5.0 m
h	Intra-platoon headway	10 m
v_0	Velocity of free vehicle	22 m/s or 25 m/s
p_0	Desired velocity of platoon	22 m/s or 25 m/s
p_{ms}	Maximum platoon size	20
v_{max}	Maximum speed allowed in road	28 m/s
b_{len}	Buffer length	2000 m
o_{dis}	Out of reach distance	2000 m
t_{out}	Operation time out	180 s
$wgtS$	Weight based on comparative speed	0.2
$wgtT$	Weight based on surrounding traffic	0.2
T	Threshold to select merging vehicle	0.6

sum of all merge distances. Similar to the MCT, a shorter TTD is desirable.

- 3) *Average traffic speed*: This metric is used to understand how merge operations impact on the traffic. It is calculated as the average speed of the free flow vehicles during the merge operations.
- 4) *Merge Success Rate*: Merge success rate is another measure to compare the merging strategies. It is calculated as the percentage of successful merge operation out of all the merge attempts. A merge operation can be delayed or interrupted by the traffic. In this simulation, we have considered two parameters: operation timeout t_{out} and out of range o_{dis} to define merge success. If the merge operation takes longer than t_{out} or the merging vehicle goes far apart of the range o_{dis} due to the traffic, the operation is considered as unsuccessful. The metric merge success rate shows which strategy enhances the chance of platoon formation and which strategy drops the chance. A high merge success rate is desirable.

D. Experimental Results

1) *Experiment 1*: In the first experiment, all the three platoon merging operations are performed in the absence of any other traffic. Here, only a single platoon of seven vehicles and a single vehicle are considered. The front merge and the tail merge are performed in a similar way. At first, the platoon is formed and a merging vehicle is placed at a certain position relative to the platoon in the next lane. The platoon or the vehicle adjusts their speed to reach to the exact parallel merge position. Then the vehicle changes its lane in order to perform the merge. Finally, the extended platoon travels at its default speed. The middle merge requires an additional function of gap creation. This implementation performs gap creation and speed adjustment simultaneously. Once the gap is created and the vehicle reaches to the proper parallel position, the vehicle

executes lane change to perform a middle merge operation. Each of these merge operations is analyzed under different scenarios like platoon speed adjustment or merging vehicle speed adjustment, and platoons having higher speed or the merging vehicles having higher speed.

During the merge operation vehicles follow the same dynamics mentioned in Table I. Vehicles can accelerate or decelerate 3 m/s^2 at max. The maximum speed limit is 28 m/s . Figure 3 shows an example of speed variation of the merging vehicle and the platoon during the merge operation. The label shows the distance of the merging vehicle and back part of the platoon (for middle merge) from the merge position in each time stamp. In the first case of the front merge, the

Fig. 3. Speed profile of merging vehicle and platoon during merge operation

platoon precedes to the merging vehicle. So, the merging vehicle speeds up to reach the merge position whereas, the platoons moves at a constant speed. In the next case of the tail merge, the merging vehicle precedes to the merge position. Therefore, the merging vehicle travels at a lower speed in order to reach the merge position and platoon maintains its speed. In the third case of the middle merge, the platoon precedes to the merging vehicle, so the merging vehicle speeds up to reach to the merge position. At the same time, the back portion of the platoon slows down compared to the front portion in order to create the gap. In all the cases, once merge operation is completed, the platoon starts moving at its default speed.

Figure 4 shows the variation of merging time of front, middle and tail merge based on the distance of the initial position of the vehicle. The distance is considered as positive if the merging vehicle is ahead of the merge position, and negative if the merging vehicle is behind the merge position. Figure 1 shows an example of positive distance dis_{FV} and negative distance dis_{BV} for front merge. Here the positive and negative distances are interpreted with respect to the platoon leader V_{pl} . Similarly, for middle and tail merge the positive and negative distances are computed with respect to middle and end platoon members respectively. In Figure 4, the legend names are abbreviated based on the test condition as ‘speed Adjustment of Platoon or Vehicle (AP/AV) - Platoon or Vehicle has Higher speed (PH/VH)’. Though the merge operation can be performed in two ways, by adjusting merging

Fig. 4. Merge time in the absence of traffic

vehicle speed and by adjusting platoon speed, the adjustment of vehicle speed and lane change are less complex. Therefore, in the next experiment, where the platoon merge operations are analyzed in the presence of traffic, only the adjustment of the merging vehicle’s speed is considered.

2) *Experiment 2:* In order to find out the most suitable merge position, we have conducted the second experiment where a vehicle merges in a platoon in different middle positions in the presence of traffic. Three different scenarios are considered as shown in Fig. 5. Here circles represent vehicles maintaining their speed, down-arrows represent vehicles slowing down, and up-arrows represent vehicles speeding up. V_p is the nearest platoon member of merging vehicle V_m .

Fig. 5. Different options of merge positions in middle merge

- 1) *Scenario 1:* The merging vehicle V_m is ahead of the platoon vehicle V_p . In case (a), both V_m and V_p can slow down, V_p creates the gap such that V_m can take the position of V_p . Case (b) describes another option, where V_p maintains its speed such that the following vehicle slows down and V_m merges behind V_p .
- 2) *Scenario 2:* In this scenario, the merging vehicle V_m is head-to-head with V_p . In case (c) V_p slows down, and V_m maintains its speed and takes the position of V_p . Alternatively (case (d)), V_p can maintain its speed, and V_m can slow down and merge behind V_p .
- 3) *Scenario 3:* In this scenario, V_m is in behind of V_p . One option (case (e)) is that V_p slows down and V_m speeds up and merges in front of V_p . Case (f): the other option for V_m is to slow down and merge behind V_p .

Among the above described options (b), (d) and (f) are symmetrical in a sense, in all three cases V_p maintains its speed and V_m slows down and enters behind V_p . The experimental results show slowing down of the merging vehicle and merging

in the next available position behind V_p is beneficial in terms of average merging time (26 s) and merge success rate (99.42%). Therefore, while selecting the merge position for the middle merge, the next available merge position is considered unless the merging vehicle is in behind to the platoon.

3) *Experiment 3*: In the third experiment, platoon merging operations are analyzed in the presence of traffic. The platoon is generated in the same way as before. But instead of considering a single merging vehicle, 300 vehicles are added, and 25% of these free flow vehicles (i.e., 75 vehicles) are considered as platoonaable. This implies 25% vehicles of the total traffic have communication capabilities and willing to be a part of platoon. The vehicles are placed in the network according to a pseudorandom distribution function. Both the platoon and the vehicles are initialized with a speed of 25 m/s. The speed of the free flow vehicles is further adapted by the IDM model. The platoon moves with constant speed unless its speed is impeded by vehicles ahead (since the platoon lead vehicle is also adapting the platoon speed by the IDM model). In each simulation step, based on the merging strategy the most suitable merging vehicle is identified. Once the merging vehicle is identified, its speed is adjusted in consecutive steps in order to reach the proper merge position. If the merging vehicle is obstructed by the platoon or if the platoon is obstructed by the merging vehicle, the merging vehicle performs a lane change and tries to reach the merge position. The experiment is run in three scenarios.

- 1) *Platoon is nearly complete*. The initial platoon length is 17. Only three merge operations are performed.
- 2) *Platoon is half complete*. The initial platoon length is ten. Ten consecutive merge operations are performed.
- 3) *Platoon in initial state*. The initial platoon length is three. 17 consecutive merge operations are performed.

For each scenario, 20 test cases are considered to compute MCT, TTD and average traffic speed.

Tab. II shows the comparison of average MCT, TTD, and the average traffic speed for the front, middle, and tail merge in the presence of traffic. MCT per merge implies how much time a single merge operation takes on average. TTD of platoon per vehicle per merge indicates how long each platoon vehicle travels on an average to complete a single merge operation in the test scenario. The average traffic speed is calculated to understand the movement rate of traffic during platoon creation.

In order to compute the merge success rate of the merging strategies, three different traffic densities are tested in the network. In all cases, 25% vehicles are platoonaable. The comparison is shown in Table III. The Figure 6 shows a graphical representation of the experimental results.

V. DISCUSSION

There are few observable points in Experiment 1 where a single vehicle merges to a platoon without traffic.

- For the tail merge minimum merge time is 2 s when the vehicle is exactly 10 m behind (intra-platoon headway) the tail member of the platoon. In our experiment with platoon size seven, the vehicle is 40 m behind from the middle

TABLE II
MERGE COMPARISON IN TRAFFIC SCENARIO

Strategy	Initial platoon length	Final platoon length	MCT per merge (s)	TTD platoon per veh (km)	Avg speed of traffic (m/s)
FM	17	20	79	3.83	16.87
MM	17	20	59	2.38	13.76
TM	17	20	78	3.81	16.79
FM	10	20	75	1.80	24.81
MM	10	20	64	1.50	24.44
TM	10	20	70	1.67	24.65
FM	3	20	69	1.76	26.28
MM	3	20	57	1.47	26.23
TM	3	20	58	1.49	26.23

TABLE III
MSR OF MERGE OPERATIONS

Total traffic (Veh/km)	MSR		
	FM (%)	MM (%)	TM (%)
200 (8)	98.70	98.70	98.70
300 (11)	98.70	99.35	98.70
400 (15)	98.70	100	97.51

Fig. 6. MCT, TTD, average traffic speed and MSR in presence of traffic

member. It is the most favorable position for tail merge. Also, the merge time is minimum when the vehicle speed is adjusted either for platoon having the higher speed or for the vehicle having higher speed. When the platoon's speed is adjusted the operation takes more time (3 s), since the platoon first adjusts its speed with the vehicle, then performs the merge, and then adjusts its speed again to default speed.

- The pattern of the merge time of front merge is exactly the same as the pattern of the tail merge. For front merge the most favorable scenario is when the vehicle starts 10 m ahead of the platoon leader.
- In middle merge, minimum merge time is 6 s when the merging vehicle is parallel to the middle position or 10 m behind or ahead of the middle position. Even if the vehicle is in exact merging position, it has to wait until the gap is created. As the gap creation and speed adjustment are performed simultaneously, the merge time is the same for the mentioned scenarios with respect to the parameter values under consideration.

- For middle merge, adjustment of vehicle speed (instead of the platoon speed) is preferable as the merge time is lesser.
- In the most favorable positions, the tail merge and front merge takes 2 s to merge, whereas, the middle merge takes 6 s to merge. The merge times support the hypothesis that, for the same distance, the middle merge is costlier with respect to the merge time.
- With no other traffic, the best merging option depends on the position of the merging vehicle. For example, if the vehicle is parallel to the middle position, then middle merge takes 6 or 7 s, but front or tail merge take 17 or 18 s. Even if the platoon is small, the vehicle has to cover an additional 20 m to perform front or tail merge. It costs 12 s in the best case. Therefore, in this case, the middle merge is preferable.
- For all three types of merging, the merge time is proportional to the distance of a vehicle.

The observed results are expected and explainable, which ensures the correctness of the implemented model and serves as validation. The observable points of Experiment 3 considering an enhanced model with traffic are as follows.

- It has been already noted that the middle merge is more expensive in terms of merge time in the ideal scenario of no traffic. In contrast, in the presence of traffic, the middle merge has the least average MCT for the test cases under consideration. The reason behind this is while selecting the preferred mergeable vehicle, for middle merge there are multiple options for merge positions, and vehicles on the level with the platoon are always close to one. For tail merge and front merge only a single merge position is available, and that one is not always so close. Furthermore, for platoons, the likelihood that a mergeable vehicle is on the level is increasing with the length of the platoon.
- The MCT of the merge operations depends on the lane numbers of the network. It has been observed that lesser lanes cause higher MCT and vice-versa. For example, the average middle merge time per vehicle are 102 s, 77 s, 70 s respectively for a two-and-three, a three-and-four, and a four-and-five lanes network. In this test scenario, the traffic is distributed initially into two lanes to maintain the identical situation. It is also noticed that if only a two-and-three lanes network is considered, the flow of free flow vehicles are obstructed during the merge operation. It results in denser traffic behind the platoon and lighter traffic ahead of the platoon. In this situation, tail merge becomes difficult and the merge success rate drops.
- The result shows that in traffic the minimum average merge time is around one minute, which is significantly higher than in the no-traffic scenario. The cause for this increment is, in traffic the speed of both the merging vehicle and the platoon are impeded by surrounding traffic. Furthermore, only 25% of the entire traffic is mergeable. So, mergeable vehicles may need to travel longer times to reach the merge position. For validation of this explanation, the middle merge operation has also been simulated with 50%, 75% and 100% mergeable vehicles. The average merge time changes drastically to 35 s, 20 s, and 15 s converging to merge times of vehicles with no traffic around.

- Experiment 3 shows the TTD of the platoon is proportional to MCT. Therefore, the middle merge can complete by traveling shorter distances, which is desirable.
- Though middle merge looks beneficial from MCT and TTD perspective, the opposite is observed with average traffic speed. For middle merge, the traffic is more impacted and travels with lower speed on average. In comparison, front and tail merge allow the traffic to move with higher speed.
- Table III shows on that, on average, MSR is also better for middle merge strategy. With the increase of traffic density, MSR decreases or stays constant for tail and front merge. Whereas, for middle merge the success rate increases.
- The experiment shows also that a merge operation fails when the selected merging vehicle is not able to reach to the merge position due to traffic, or when no mergeable vehicle is in range. In most of the failed cases with selected merging vehicles, these vehicles were trying to merge from behind. Here, the merging vehicle needs to speed up to reach merge position but has been impeded by surrounding traffic. When a front vehicle is selected, it needs to slow down to reach the merge position, and this is less impeded by surrounding traffic, leading to higher success rate in the merge.
- The experiment is conducted for a particular vehicle speed 25 m/s. While a variation of speed may lead to an increase or decrease of MCT, the impact is the same for all the merge strategies. For example, for the speed 22 m/s the average MCT changes to 58 s, 46 s, and 48 s for front, middle and tail merge where ten merge operations are executed. Therefore, we can say the trend of the merge strategies remains the same for different speed profiles.

VI. CONCLUSION

Our research analyzes different platoon merging strategies. Three merge operations, namely front merge, middle merge and tail merge are performed in the absence of traffic, and in presence of traffic, under different scenarios. The scenarios include a variation of vehicle and platoon speed, and speed adjustment of either platoon or vehicle. The experimental results support the hypothesis that in the absence of traffic, the vehicle merge time is proportional to the distance of the vehicle. For the same distance, the merge time of middle merge is higher than tail merge or front merge. The analysis validates the correctness of our proposed model.

In the next phase, the basic model is enhanced and the merge strategies are analyzed in the presence of traffic. In this phase, a heuristic is proposed to select the most preferable merging vehicle. The experiment is performed for three sets of test cases considering a platoon in a nearly complete state, a platoon in half complete state, and a platoon at an initial state. The research reports that for the given test scenarios, the middle merge is more preferable in terms of merge completion time, platoon travel distance, and merge success rate. On the flip side, the middle merge impedes the average traffic speed more compared to the other two merging operations.

Therefore, platoons should adapt the more appropriate merge operation on a case-by-case basis. In principle, a merge operation should be chosen based on the objective, for

example, to minimize MCT or TTD, or to maximize merge success rate or average traffic speed.

Overall, the research provides a platooning model to test various scenarios with or without traffic. As a performance metric, the research has considered merge completion time, total travel distance, average traffic speed and merge success rate. Whereas, the analysis of fuel consumption during the operation is targeted as future research. As of now, only platoon merge operations are analyzed; other platoon operations such as platoon split should also be analyzed, in order to investigate a platoon's complete life cycle. Consideration of vehicles' destinations in the merge process is also left for future work.

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