Analysis of an Ad-hoc Platoon Formation and Dissolution Strategy on a Multi-lane Highway

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Abstract

Vehicle platooning has become popular in the recent Intelligent Transportation System (ITS) research. The literature typically assumes a planned formation and dissolution of platoons, mostly at source and destination. In contrast, this research considers platoons that can be formed on the fly. We investigate a greedy type of platoon formation with no particular order of destinations of the platoon members. This greedy formation allows a quick formation of the platoon but imposes an overhead of platoon rebuild cost when platoon members leave. The question arises whether this greedy formation and dissolution of platoons can preserve the original fuel benefit of platooning. To investigate this question, this research implements such a strategy and provides a generic guideline for fuel-efficient ad-hoc platooning.

Keywords: Vehicle platooning, Ad-hoc formation, Formation strategy, Fuel efficiency.

1 Introduction

Vehicle platooning, a coordinated and controlled vehicle-following strategy, addresses the issue of high fuel consumption of heavy-duty vehicles (HDV). On highways, air resistance influences a vehicle's fuel consumption significantly. A shorter gap between vehicles reduces the air resistance, thus can save fuel (Nowakowski et al., 2015). Previous studies have shown that platooning can save up to 4% of fuel for the front vehicle, and 10% of fuel for the following vehicles (Turri, 2015). Other than the fuel efficiency, the coordination and control strategy of platoons makes better utilization of space, enhances road capacity, and ensures road safety.

The literature so far tested a *planned* way of platoon formation, mostly at source or at highway ramps, and platoon dissolution at the destination (Bergenhem et al., 2012). In contrast, this research considers a greedy *ad-hoc* platoon formation where the free-flowing vehicles can form platoons on highways on the fly. In this more flexible approach, formation and dissolution requires often a higher fuel expenditure due to making up leeway and adjusting speeds. For a short lifespans of ad-hoc platoons the fuel benefit from forming a platoon may not amortize that fuel expenditure. Thus,

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it is important to analyze the proposed ad-hoc strategy to identify under which circumstances the vehicles' platoon could be fuel efficient and when the vehicles should travel independently.

Platoon formation so far considered merge operations either at highway entry ramps, or by vehicles entering the highway from a ramp with vehicles travelling already on the highway. In these strategies, vehicles with common or close destinations form platoons, so that the platoons stay intact for longer distance. A work by Liang (2016) even considered ad-hoc platoon formation on the highway. But it assumed that the operational costs of formation are negligible compared to the benefits of platooning over long travel distances, while in reality the common travel distances may not always be long. Hence, the operational costs cannot be ignored.

In this paper, we analyze an ad-hoc platoon formation strategy, namely a greedy platoon formation where the vehicles are joining based on their current position. During the platoon formation, the destinations of the vehicles are not considered. Therefore, upon arrival at a destination ramp, members may leave the platoon from any position, also from the middle. Thus this strategy enables a quick platoon formation. But it imposes an overhead of platoon rebuild cost after dissolution that impacts on the fuel benefit of the platoon. As this greedy ad-hoc formation strategy has some positive and negative impacts, we implement and evaluate the strategy in a simulation environment to determine if the strategy outperforms the non-platooning free-flow traffic scenario.

Hypothesis: The hypothesis for this research is that the ad-hoc greedy formation of vehicle platooning can be beneficial compared to non-platooning. The support for this hypothesis will then also suggest guidelines for the formation in a given traffic situation.

The objective of this research is to ensure the fuel benefit of ad-hoc platooning in a multi-lane highway. Hence, the key contributions will be:

1. a model and implementation of the greedy ad-hoc platoon formation and dissolution strategy in a multi-lane highway, which has not been tried before.
2. an analysis of fuel efficiency of the proposed formation strategy.
3. guidelines when to form platoons in an ad-hoc manner.

Section 2 provides a brief review of different platoon formation strategies. Section 3 describes the basic modules of our proposed methodology. Section 4 presents the simulation. Our findings and the key insights are presented in Section 5. Section 6 concludes the paper.

2 Literature Review

The proposed types of platoon formations can be broadly classified as *ramp-based formation* and *ramp-highway-based formation*. In ramp-based formations (Hall and Chin, 2005), 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. The four types of ramp-based formation strategies are destination grouping, dynamic grouping, dynamic grouping and platoon splitting, and random formation. All the ramp-based formation strategies demand extra time to form the platoon at the ramp. An alternative way of formation is ramp-highway-based platoon formation includes optimized platoon formation and transient platoon formation. The transient platoon formation strategy enhances the time a vehicle is a part of a platoon, while it compromises the platoon stability.

In all these strategies, only *tail merge* is required as the formation is restricted at the ramp or the ramp and highway junction. Whereas, in a floating traffic of multi-lane highway, more flexible platoon operations are desired where the merging vehicle can request for merge from the back, the front, or the side of the platoon (Maiti et al., 2017). These flexible platoon operations open up different options of platoon formation which are beyond the above-mentioned formation strategies.

Apart from this, in (Meisen et al., 2008) data-mining techniques are used to mine frequent sub-routes to plan and organize platoon formation. Larson et al. (2015) used controllers at the junctions of the road network to coordinate and reroute vehicles in order to form platoon in a fuel-efficient way. Also, a centralized coordination scheme is proposed to form platoons at junctions based on each vehicles shortest path to its destination (Van De Hoef et al., 2015). In contrast to all these strategies, our proposed methodology provides vehicle selection technique from a randomly distributed traffic to form platoons in an ad-hoc greedy manner and analyzes potential fuel saving.

Platoon formation strategies have been mainly implemented and evaluated in Verkehr In Stadten - SIMulationsmodel (VISSIM) simulation platform (Fellendorf and Vortisch, 2001). Platooning of autonomous vehicles has also been tested in Simulation of Urban MObility (SUMO) simulation platform (Fernandes and Nunes, 2010). Amoozadeh et al. (2015) tested the platooning scenarios in the integrated (SUMO and OMNET++) simulation platform VEhicular NeTwork Open Simulator (VENTOS). In this research, we have omitted any Vehicle to Vehicle communication protocol. Therefore, SUMO is used as the simulation platform and MATLAB is used as the external controller. This setup is sufficient to carry out the experiments under consideration.

3 Proposed Methodology

Our research uses a microscopic traffic simulation as we aim to control and observe parameters such as vehicle speed, acceleration, relative position, and fuel consumption in a platoon. This section describes the basic blocks of our proposed methodology that includes a model for car-following, lane change, fuel consumption, and platooning.

3.1 Car-Following Models

A car-following model controls a vehicle's longitudinal movement. In our simulation, we have two types of vehicles, free-flow vehicles of traffic and the vehicles moving as a platoon. In Intelligent Driver Model (IDM), the speed of a vehicle is adjusted according to the preceding vehicle to avoid the collision (Treiber et al., 2000). So, this model is suitable for simulating the free-flow traffic. The platoon leader also adopts the IDM car-following model. But the follower vehicles need to keep a constant distance, which is shorter than the safe distance of free-flow traffic. Therefore, the platoon followers adopt the platoon leader's speed to maintain a constant headway. Other micro-effects such as communication delay or disturbances are not accounted for in this simulation.

3.2 Lane Change Model

A lane change model controls a vehicle's lateral movement. This simulation uses the default lane change model of SUMO traffic simulator, LC2013, to handle the lane change of free flow vehicles. According to this model, a vehicle performs lane change when it is obstructed by preceding vehicles and parallel lanes are free or when the lanes merge to a lesser number of lanes. On the other hand, a platoon performs a lane change if it is safe to move the entire platoon to the next lane without causing any crash.

3.3 Fuel Consumption Model

Fuel consumption refers to the fuel needed to maintain the engine operation, the energy consumed by the vehicle engine for movement, the product of energy and acceleration during periods of positive acceleration, energy consumption due to the drag, inertial, and the gradient components. Most of the models use average vehicle speed and a regression model for estimation (Tong et al., 2000; Cappiello et al., 2002). This simulation considers the microscopic approach of simulation, where the speed adjustment in each instance during the catch-up, impacts platoon's fuel benefit. Therefore, we use an instantaneous fuel consumption model (Bowyer et al., 1985), where the fuel consumption is calculated based on instant vehicle speed, acceleration, and gradient of the road.

3.4 Platooning Model

The life-cycle of a platoon includes platooning vehicle selection from free-flow traffic, platoon formation, and platoon dissolution (i.e. membership reduction and rebuild), and platoon destroy as shown in Fig. 1. The platoon formation and dissolution strategy directly impact platoon's fuel consumption. The following section provides an overview of the important phases of platoon life-cycle.

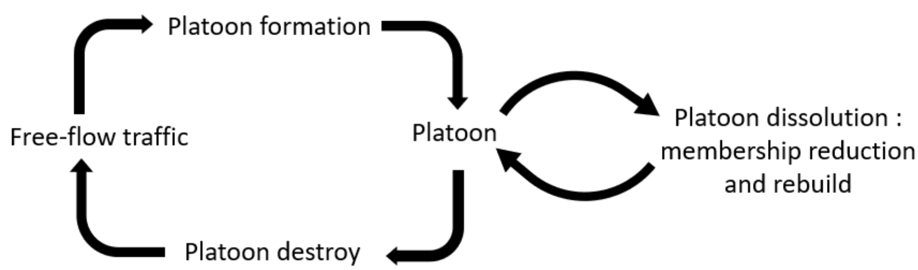


Figure 1: The life-cycle of a vehicle platoon.

3.4.1 Platooning Vehicle Selection Strategy

Not all the vehicles can obtain fuel benefit through platooning. The fuel benefit cannot be realized if the platooning vehicles are far away such that the fuel consumption for the catch up is more than the platoon's fuel benefit. Also, if the members join the platoon for a short time then the platoon may not show fuel efficiency. Therefore, it is crucial to identify vehicles from the traffic that can provide potential fuel benefit from being a platoon.

To identify the fuel-efficient vehicles, we perform clustering followed by classification of free-flow traffic. Here, the number of clusters is not pre-determined; it mainly depends on the density of the vehicles at any location. So, a density-based clustering algorithm DBScan (Ester et al., 1996) is used to identify the connected vehicles that are in communication range. The connected vehicles are further classified using a standard classification model SVM (Support-Vector Machine). Three parameters, namely the inter-vehicle distance, the last platoonable point distance (the maximum distance the vehicles can travel as a platoon), and the speed difference of the vehicles are considered as the feature set and fuel benefit and loss are considered as classes to train the SVM classification model. The simulation results of two vehicles are considered as training dataset. The model learns the parameter combinations where platooning is efficient. Finally, the trained SVM model predicts if a platoon of two vehicles of a cluster will be fuel efficient or not. If the model predicts fuel benefit, then both vehicles are assigned to the same sub-cluster, otherwise, to different sub-clusters. A vehicle with no fuel benefit is not assigned further to any sub-cluster. From each sub-cluster, a platoon is formed.

3.4.2 Greedy Ad-hoc Platoon Formation

Once vehicles are selected, their speeds are adjusted to form platoons on highways. In this formation strategy, a platoon is formed only based on the longitudinal positions of the vehicles. The leading vehicle towards the movement direction is selected as the platoon leader. The other vehicles are inserted into the platoon as platoon followers based on the descending order of their positions.

- Step 1: We select the leftmost lane for platoon movement. So, first, the platoon leader moves to the leftmost lane if it is not there already. The vehicles change their lanes and move to the platoon leader's lane.
- Step 2: During the lane change if two vehicles are found in different lanes but close in position, then the succeeding vehicle slows down to make space for the preceding vehicle. If two vehicles are exactly in the same position, then the vehicle with nearer destination slows down.
- Step 3: After all vehicles of the sub-cluster moves to the same lane, the formation process starts.
- Step 4: We select the first pair of vehicles. From the pair, the preceding vehicle slows down and the succeeding vehicle maintains its speed to reduce the inter-vehicle distance.
- Step 5: Once the inter-vehicle distance is near to the desired intra-platoon gap; the preceding vehicle speeds up to achieve the succeeding vehicle's speed to form a platoon of size two.
- Step 6: From the sub-cluster, the nearest vehicle to the platoon is selected to merge with the platoon next. Again, the preceding one, the platoon slows down to perform the merge operation. The process repeats until all the vehicles of a sub-cluster merge and form a single platoon. From all the sub-clusters platoons are formed parallelly.

After the formation, the platoons move towards the destination ramps with the desired speed.

3.4.3 Platoon Dissolution

As the platoon moves through the highway, some of the platoon members approach to their destination ramps. These members leave the platoon which may result in a number of sub-platoons for time being. Later, the remaining vehicles adjust their speeds to reduce the extra space created due to members' leave and rebuild the platoon. The exit of the platoon members results in different scenarios as follows.

1. *Exit of platoon leader*: If platoon leader leaves the platoon, the leader turns into a free-flow vehicle of traffic. The next vehicle among the remaining platoon members becomes the new platoon leader.

2. *Exit of middle member*: If a middle member of platoon leaves the platoon, the next member turns into a temporary leader or free-flow vehicle until the platoon rebuild process completes. Once the rebuild process completes, the remaining vehicles next to that left middle member turn back to platoon followers.

3. *Exit of platoon followers from back*: When one or more platoon followers leave the platoon from back, the role of the other members remain the same.

As the percentage of fuel-saving depends on the role of a vehicle, it is important to change the remaining platoon members' role correctly when some of the members leave the platoon.

4 Experiment

This section presents a detailed description of the simulation. To make the simulation model simple, we assume the same characteristic of all vehicles, constant weather and a standard road condition.

4.1 Experimental Setup

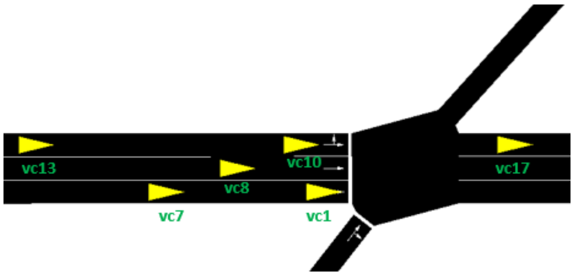
All experiments are carried out in the open source traffic simulator SUMO (Simulation of Urban MObility). MATLAB is used to control the vehicles externally. Here, TraCI (Traffic Control Interface) (Acosta et al., 2015) works as the interface between MATLAB and SUMO. To simulate the platoons and the traffic, a 60 kilometer long straight three-lane highway traffic network is designed. The network consists of 30 segments of 2 km length each. In each segment, there is an entry ramp and an exit ramp. The parameters and their values used in the platoon simulation are listed in Table 1. These are the standard settings that are typically used in the literature (Hobert, 2012). This research uses fuel consumption as an evaluation metric. The instantaneous fuel consumption model described in Sec. 3.3 is used to compute the fuel consumption of vehicles both for platooning and non-platooning.

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	7.0 m
h	Intra-platoon headway	10 m
v	Desired velocity of platoon and free vehicle	28 m/s
v_{max}	Maximum speed allowed in road	28 m/s
v_{min}	Minimum speed preferred in road	16 m/s

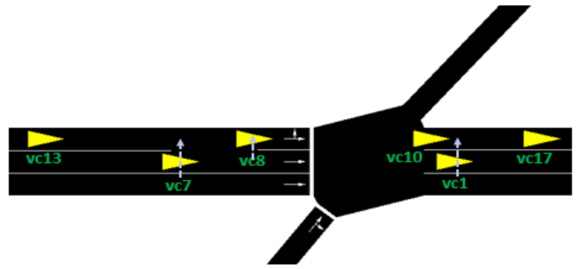
Table 1: Parameters used in the platoon simulation.

4.2 Description of the Simulation

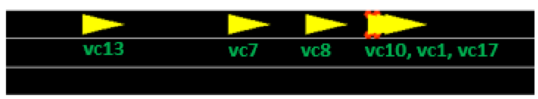
Platoon formation and dissolution are two important phases of the platoon's life-cycle. An illustration of the formation strategy is shown in Fig. 2.



(a) Initial vehicles sub-cluster



(b) Platoon members getting their positions - lane change



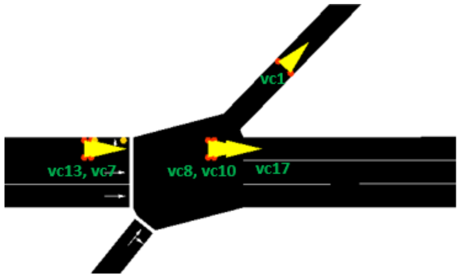
(c) Platoon formation - speed adjustment

Figure 2: Ad-hoc platoon formation by a greedy strategy.

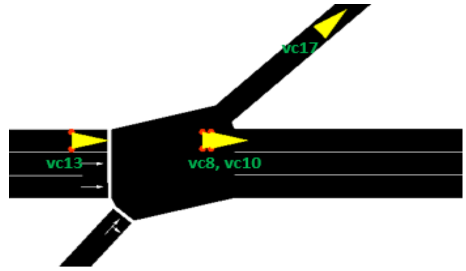
From traffic, six vehicles vc_{13}, vc_7, vc_8, vc_{10}, vc_1, and vc_{17} are selected and assigned to a sub-cluster (Fig. 2a). The leading vehicle vc_{17} is selected as platoon leader. Other five vehicles are considered as platoon followers. Platoon leader vc_{17} and other two vehicles vc_{10}, vc_{13} are already in left most lane where the platoon will be formed. Therefore, those three vehicles do not change their lanes. Other three vehicles vc_1, vc_8, and vc_7 shift left in consecutive simulation steps to get positions in platoon (Fig. 2b). Once all vehicles are shifted to the left-most lane, we identify the first vehicle pair vc_1, vc_{17}. vc_{17} slows down to perform the merge operation. The next nearest vehicle vc_{10} is selected to perform next merge operation. Consecutive merge operations are performed to form the complete platoon as shown in Fig. 2c. The complete platoon forms as $(vc_{13}, vc_7, vc_8, vc_{10}, vc_1, vc_{17})$, vc_{17} as platoon leader and vc_{13} and last member.

The platoon dissolution starts when one or more platoon members reach their exit ramp. Fig. 3 illustrates a platoon dissolution.

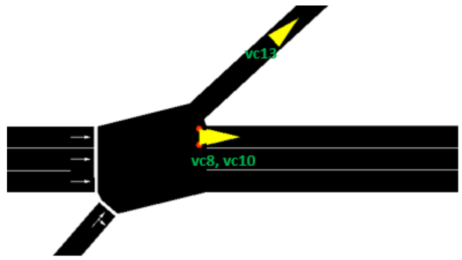
In this example, two platoon followers vc_1 and vc_7 approach to their exit ramp first. In the six-vehicle platoon, vc_1 is the second and vc_7 is the fifth member. As, vc_1 leaves the platoon (Fig. 3a), the platoon leader vc_{17} turns into free-flow vehicle temporarily. vc_{10} turns into platoon leader of the sub-platoon $(vc_{13}, vc_7, vc_8, vc_{10})$. Next, when vc_7 leaves, the last member vc_{13} turns into free-flow vehicle. The members adjust their speeds and rebuild the platoon $(vc_{13}, vc_8, vc_{10}, vc_{17})$. In next exit ramp, platoon leader vc_{17} exists and vc_{10} becomes new platoon leader (Fig. 3b). The last member



(a) Platoon follower leaves platoon



(b) Platoon leader leaves platoon



(c) Platoon tail member leaves platoon

Figure 3: Ad-hoc platoon dissolution.

vc_{13} also leaves through the same exit ramp (Fig. 3c). It does not make any change for the rest of the platoon. In the next exit ramp vc_8 exits. Along with that the platoon dissolution process completes and the platoon is destroyed.

5 Results and Discussion

We considered 20 test cases where vehicles are initialized and randomly distributed in the simulation network. The average density of vehicles is ten vehicles per km. Once all vehicles moved into the highway, we apply DBScan and SVM classification to cluster and sub-cluster the vehicles. The platoons are formed from the sub-clusters in a greedy manner. After travelling through the highway, the vehicles leave the platoon through exit ramps. We compute the fuel consumption of the vehicles that travel as a platoon and obtain the percentage of fuel savings compared to non-platooning. We do not compare the other formation strategies with the greedy strategy as they are non-ad-hoc in nature. Table 2 shows the results.

Platoon size	Fuel savings (%)
2	5.32
3	6.71
4	7.67
5	6.18
6	5.9

Table 2: Fuel saving percentages for ad-hoc greedy platoon formation

From the experimental results we observe the following:

- The percentage of fuel saving of platooning is proportional to the platoon travel distance. For the same length of a platoon, the fuel-saving percentage is higher for the platoon with higher travel distance. Experiment shows, as per the simulation setup, a platoon needs to travel at least 20 km to obtain the fuel efficiency.
- The platoon of length two is always fuel efficient. For a platoon of length two, the fuel consumption is realized only during platoon formation. There is no fuel expenditure for platoon rebuild. Therefore, platooning always turns out fuel efficient.
- The percentage of fuel-saving increases up to the platoon length four. After that, the percentage falls. As the length of platoon increases, there is more possibility of the randomness of platoon members' destinations. This demands platoon rebuild and applies to fuel cost. Therefore, the fuel-saving percentage decreases for higher platoon length.
- In 8% of the cases of ad-hoc greedy platooning was not beneficial due to shorter travel distances and the randomness of platoon members destinations. The fuel benefit obtained from a platoon when the travel distance is short cannot outweigh the fuel expenditure during platoon formation and dissolution. Most of the failure cases are observed for higher length of the platoons.

6 Conclusion

Our research investigates a platoon's life-cycle from formation to dissolution. In contrast to the existing studies, the formation and dissolution of platoons are performed on the fly. The platooning vehicles are selected through a clustering and classification process. From the sub-clustered vehicles, platoons are formed in a greedy manner based on vehicles' positions, irrespective of their destinations. Platoons are destroyed as all the vehicles leave the platoons. Our investigation focuses on the fuel efficiency of vehicles and compares platooning versus non-platooning scenarios. Our analysis shows that the greedy approach of platoon formation is beneficial compared to non-platooning scenario in most cases. A shorter platoon length and higher travel distance ensures fuel savings in platooning scenario. This research contributes towards the implementation of greedy strategies for ad-hoc platooning to ensure fuel efficiency.

The simulation can be extended in various ways. Currently, while generating a platoon, the merge operations are executed sequentially. A parallel merge operation could lead to higher fuel efficiency in platoon formation. Also, the platoons can be generated in many possible ways from given traffic. This research investigates one possible way of platoon formation and dissolution, and the corresponding fuel efficiency. An analysis of other formation strategies is planned for the future.

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