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A STUDY ON THE BEHAVIOR OF VEHICLE PLATOONS AND PLATOON FORMATION AND DISSOLUTION STRATEGIES

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Santa Maiti: *A Study on the Behavior of Vehicle Platoons and Platoon Formation and Dissolution Strategies*

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Dedicated to my family and friends.

Success is not final,
failure is not fatal:
it is the courage to continue that counts.

— Winston Churchill

ABSTRACT

Vehicle platooning, a coordinated movement strategy, has been proposed to address a range of current transport challenges such as traffic congestion, road safety, energy consumption and pollution. The current literature and on-road platooning trials typically assume a planned formation at the source and dissolution at the destination. In contrast, this research considers platoons that can be formed in an ad-hoc manner, on the fly, opportunistically. To form platoons in an ad-hoc manner the vehicles have to 'speak the same language', which is in current practice limited to vehicles of particular manufacturers. There is no standard language yet. This thesis aims to fill this fundamental gap of standardization by developing a formal model of platooning concepts. The research proposes an ontological model of platooning objects and properties and abstracts the basic building blocks of platoon operations that can then be aggregated to complex platooning behavior.

Also, the current literature considered platoon formation by tail merge which is sufficient only for the formation on a ramp or at a ramp-highway junction. In ad-hoc formation, a vehicle can express a merge request when approaching the platoon on the highway from the back, front or the side of the platoon. This thesis studies the impact of these three different merge operations, namely front merge, middle merge, 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 is 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.

As this research considers ad-hoc formations of platoons, the question arises whether the original benefits of platooning can be preserved for the ad-hoc formations. The formation is not desirable if the time the vehicles move as a platoon is too short to realize the fuel efficiency. Hence, for a vehicle, it is crucial to decide whether or not to platoon in a given traffic situation. This thesis aims to solve this decision-making problem by analyzing the situation-aware fuel efficiency of platoon formation, and building a cost prediction model. The model provides a guideline of efficient ad-hoc platoon formation.

The proposed model is evaluated using prediction accuracy, i.e. the percentage of correct prediction to form fuel-efficient platoons, out of all predictions. The experimental result shows 89.2% prediction accuracy of the proposed model.

At the final stage, this research investigates two different types of ad-hoc platoon formation and corresponding platoon dissolution strategies on multi-lane highway. Multi-lane allows the vehicle to overtake. Hence, a platoon can be formed in many different ways. The first approach forms a platoon greedily without considering the order of destinations of the platoon members. This approach enables a quick formation but imposes an overhead of platoon rebuilding, and consequently, additional fuel cost when platoon members leave. An alternative approach forms a platoon in the order of the destinations of its platoon members. This ordered approach incurs a comparatively higher formation time due to vehicles' reorganization but does not lead to further overhead of platoon rebuilding. The research investigates these two ad-hoc formation and dissolution strategies. The prediction model shows 90.4% prediction accuracy for the greedy approach and 82.2% prediction accuracy for the ordered approach on average for platoon size two to six. The experiment determines greedy formation of platoon is more fuel-efficient for multi-lane highway.

PUBLICATIONS

This thesis is based on published works and the papers under review from my PhD research during candidature. Its contents including ideas, algorithms and figures have appeared in the following publications:

Journal articles

- Maiti, S., Winter, S. and Kulik, L. (2017). A Conceptualization of Vehicle Platoons and Platoon Operations. In: *Transportation Research Part C: Emerging Technologies*, 80, pp.1-19.
- Maiti, S., Winter, S., Kulik, L. and Sarkar, S (2019). The Impact of Flexible Platoon Formation Operations. In: *IEEE Transactions on Intelligent Vehicles*.
- Maiti, S., Winter, S., Kulik, L. and Sarkar, S (2019). A Strategy of Fuel-efficient Ad-hoc Platoon Formation on a Single-lane Highway. (under review)
- Maiti, S., Winter, S., Kulik, L. and Sarkar, S (2019). Greedy and Order-based Ad-hoc Platoon Formation and Dissolution Strategies on a Multi-lane Highway. (under review)

Peer-reviewed conference article

- Maiti, S., Winter, S., Kulik, L. and Sarkar, S (2019). Analysis of an Ad-hoc Platoon Formation and Dissolution Strategy on a Multi-lane Highway. 15th International Conference of GeoComputation 2019.

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ACRONYMS

CO_2 Carbon Dioxide

NHTSA National Highway Traffic Safety Administration

ACC Adaptive Cruise Control

CACC Cooperative Adaptive Cruise Control

PATH Partners In Advance Transportation Technology

ITS Intelligent Transportation Systems

SARTRE Safe Road Trains for the Environment

MITSIM Microscopic Traffic Simulator

MATSIM Multi-Agent Transport Simulation

SUMO Simulation of Urban Mobility

TRANSIMS Transportation Analysis and Simulation

VISSIM Verkehr In Städten Simulations Model

GPL General Public License

TraNS Traffic and Network Simulation Environment

TraCI Traffic Control Interface

MATLAB Matrix Laboratory

TCP Transmission Control Protocol

NETEDIT Network Editor

VENTOS Vehicular Network Open Simulator

VEINS Vehicles in Network Simulation

PLEXE Platooning Extension of VEINS

DL Description Logic

MCT Merge Completion Time

TTD Total Travel Distance

MSR Merge Success Rate

IDM Intelligent Driver Model

DBSCAN Density-Based Spatial Clustering of Applications with Noise

SVM Support Vector Machine

DSRC Dedicated Short-Range Communications

1 INTRODUCTION

Vehicle platooning, a coordinated movement strategy, has been proposed to address a range of current transport challenges such as traffic congestion, road safety, energy consumption and pollution. In vehicle platooning, a group of vehicles are allowed to drive with a short inter-vehicular distance. The shorter gap between vehicles results in less aerodynamic drag and hence, lower fuel consumption. The closer headway between vehicles also reduces congestion by increasing the road capacity. Besides, the efficient control mechanism of the platooning system requires less reacting distance compared to human reaction and allows vehicles to accelerate or brake simultaneously. Hence, platooning reduces the chance of accidents and enhances road safety. Despite of several benefits, vehicle platooning is still confined within vehicles of particular manufacturers as the operations and coordination of platoon are not yet commonly agreed. To form platoons in an ad-hoc manner, the vehicles have to 'speak the same language' and to follow common standard protocols. More precisely, ad-hoc platooning requires an agreement on the conceptualization of platooning objects and platoon operations. Also in research, while different research groups and vehicle manufacturers explored various aspects of platooning such as the platoon control strategy, communication and coordination, the platoon management protocol, and platoon safety measures, a gap is noticed towards the analysis of platoon behaviors, specifically, platoon formation and dissolution strategies and their impact on traffic. This thesis addresses the mentioned research gaps.

This chapter is organized as follows. Section 1.1 describes the background of vehicle platooning. The proposal and purpose of vehicle platooning are presented in Section 1.2. The research gaps and associated research scopes are discussed in Section 1.3. Section 1.4 describes the research challenges addressed in this thesis. Finally, the significance of the study and the outline of the thesis are presented in Section 1.5 and Section 1.6.

1.1 BACKGROUND

With global urbanization, the continuous growth of travel demand is observed all over the world, both for passenger transport and freight transport (Bayliss, 2008). As a consequence, we can observe more motor vehicles on the road, and vehicles are travelling for long distances. Figure 1 shows the growth of the number of passenger vehicles and

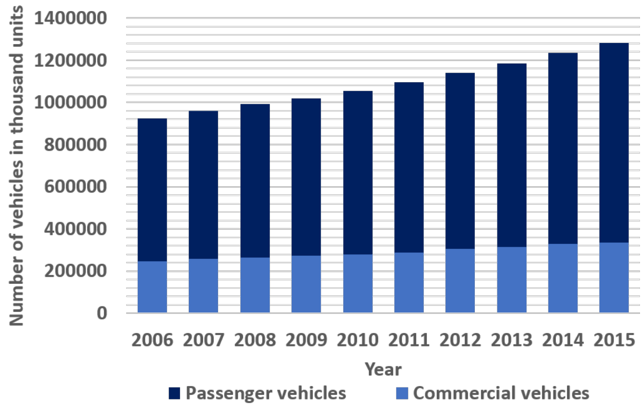


Figure 1: Number of vehicles in use worldwide from 2006 to 2015.[1]

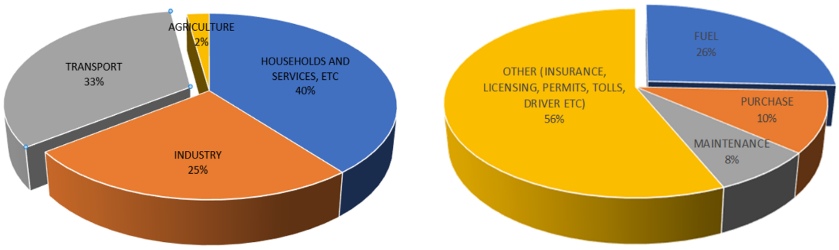
commercial vehicles in use worldwide from 2006 to 2015.[1] In 2015, around 947 million passenger cars and 335 million commercial vehicles were in operation worldwide. Researchers estimated that the world's motor vehicle count would reach 2 billion by 2020 (Sousanis, 2011; Sperling and Gordon, 2010).

The growth of vehicles has adverse effects on society and environment. It increases fuel consumption, air pollution, congestion, and the number of accidents (Deng, 2016). To eliminate the direct dependency on fuel, the electric vehicles will replace the fuel-based vehicles in future. But, it is predicted that the oil will likely remain the primary fuel for vehicles specially for light-duty vehicles for the next two decades (Albrahim et al., 2019). Transport and European Communities shows that the transport sector consumes around 33% of the global energy (Figure 2a) and most of that comes from fossil fuel. Now, fossil energy sources are limited. Although the technology is moving towards the production and use of renewable energy, it is far away to replace fossil energy completely. A statistical report of International Energy Agency (Agency, 2019) shows that in 2017, the world's primary energy supply is from oil (32%), followed by coal (27.1%), natural gas (22.2%), biofuels and waste (9.5%), nuclear (4.9%), hydro (2.5%), and others (renewables) (1.8%). Therefore, the higher energy consumption of vehicles associates with higher expenses. Currently, at least 26% of the total expenditure (Figure 2b) of owning and operating a vehicle is expended for fuel (Meszler et al., 2018). Hence, a reduction the fuel consumption by a few percentages can lead to a significant saving for the transportation sector.

From the perspective of emission, the road transportation was accounted for 23% of the total human-related Carbon Dioxide (CO_2) emissions (Figure 3) in 2015 (Transport and European Communities,

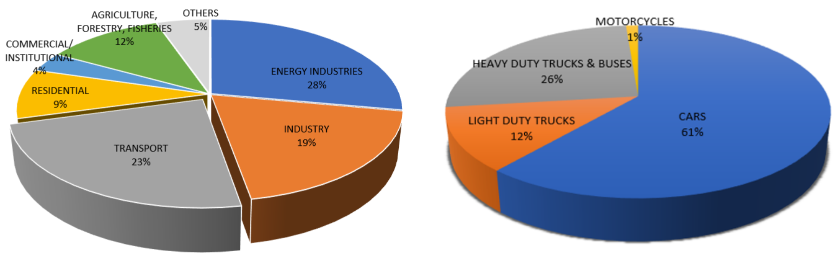
1 Statista, https://www.statista.com/statistics/281134/number-of-vehicles-in-use-worldwide/, accessed July 14, 2019,

2017). Though the emissions from other sectors have dropped in the last 30 years, the emission from road transport is still on the rise. Due to the economic dependency of the transport sector, it is expected to continue to expand. Other than CO_2, the transport sector emits non-CO_2 pollutants that also affect climate.



(a) Energy consumption by sectors (b) Operating cost of vehicle

Figure 2: Percentage of energy consumption in European Union, 2015 (Transport and European Communities, 2017) and percentage of fuel expenditure for operating a vehicle (Meszler et al., 2018).



(a) CO_2 emissions by sectors (b) CO_2 emissions by vehicle categories

Figure 3: Percentage of the CO_2 emissions in European Union, 2015. (Transport and European Communities, 2017)

Moreover, the growth of vehicles has also caused an increase in congestion in recent years. It is estimated that the annual congestion cost in the United Kingdom will reach 33.4 billion US dollars by 2030, rising by over 50% from the 2014 levels of 20.5 billion US dollars. Similarly, the annual cost of congestion in the United States as of 2014 has been pegged at 124 billion US dollars; this is projected to increase to 186 billion US dollars by 2030 (Carey and Srinivasan, 1993; Davis et al., 2017). The congestion not only affects the inner-city traffic flow, but it also blocks the highway traffic. For example, the China National Highway 110 traffic jam in Hebei province in August 2010 stretched more than 100 kilometres and created gridlock for 11 days.[2] This congestion was caused by a combination of road works and thousands of coal trucks from Inner Mongolia's coalfields that

2 The New York Times, https://www.nytimes.com/2010/08/28/world/asia/28china.html, accessed August 2, 2019

travel daily to Beijing. In another scenario, 22 people died because of carbon monoxide poisoning, fatigue or heat as a result of traffic congestion in Java, Indonesia in July 2016.[3] The traffic block stretched for 21 km and thousands of cars clogged the highway for three days. The severity of the congestion and corresponding costs caught transport authorities' attention and needs immediate action.

Along with the congestion problem, road transport is accountable for a significant number of accidents. As per the global status report on-road safety, the number of annual road traffic deaths has reached 1.35 million in 2018 (Organization and Others, 2018). Immediate action is needed to put these measures in place to save lives.

This increasing demand for cheap, fast and effective transportation services has compelled the transportation industry to look for reliable, cost-effective and sustainable practices. Due to the high level of emissions, regulations for environmental protection become more stringent. Hence, for the vehicles, in particular for heavy-duty vehicles, it becomes necessary to adopt new practices to remain sustainable in terms of business as well as societal well-being.

1.2 VEHICLE PLATOONING

To provide a sustainable, energy-efficient, and safer transportation system, researches and road authorities investigated different technologies that will shape the future of mobility. Several solutions have been proposed in the last few years. Some initial solutions (Hobert, 2012) suggested an increment of road capacity by creating more roads and lanes, encouraging people for using public transport and ride-sharing or encouraging drivers to drive outside the rush hours. Another solution has been proposed to charge drivers for road usage. All these solutions address the issues mentioned above only upto some extent.

To reduce the number of accidents on the road, researchers proposed autonomous vehicles controlled by automated driving systems. These vehicles are capable of sensing the environment and moving safely. Here, the perception, decision making, and operation of the automobile are performed by electronics and machinery instead of a human driver. The National Highway Traffic Safety Administration (NHTSA) defined the levels for automation, ranging from complete driver control to full automation (Administration et al., 2017; Automated Vehicle Standards Committee et al., 2014). Recently, SAE International published a new visual chart to clarify and simplify the levels of driving automation standard as shown in (Figure 4).

3 The Guardian, https://www.theguardian.com/world/2016/jul/08/indonesia-traffic-jam-deaths-java-brebes-brexit-junction, accessed August 2, 2019

4 SAE International, https://www.sae.org/news/2019/01/sae-updates-j3016-automated-driving-graphic, accessed March 1, 2020

Figure 4: Levels of driving automation.[4]

Automation makes the vehicle control system efficient. Driver assistance systems of Level 1 automation offer to assist drivers on the road using the advance information and communication technologies (Van Driel and Van Arem, 2010). In the same of level automation, Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) have been proposed. ACC improves the traffic flow by keeping the desired time-gap to the preceding vehicle. Wireless communication of CACC enables cooperation between vehicles (Nowakowski et al., 2015). Though CACC is introduced in Level 1 in Figure 4, it provides the contact between vehicles at all levels up to Level 5. The cooperation and control of vehicles are improved in the upper levels of automation. Based on this advancement of vehicle automation, cooperation and control systems, researchers proposed vehicle platooning to address the transportation related challenges.

Vehicle platooning concept can be defined as a collection of vehicles that travel together, actively coordinated in formation (Bergenhem et al., 2012). Figure 5 shows an example of a vehicle platooning of four heavy-duty vehicles: one platoon leader and three platoon followers. A vehicle platoon generally consists of one platoon leader and several platoon followers. The platoon leader makes decisions on behalf of the whole platoon and controls the platoon members accordingly. On highways, air resistance influences a vehicle's fuel consumption significantly. A shorter gap between vehicles creates a tunnel of air that moves at a lower relative speed with respect to the platooning vehicles. This results in a reduction of aerodynamic drag for all the following vehicles and also for the leading vehicle in a smaller quantity. As a consequence, platooning saves fuel and reduces the emission of greenhouse gas and other non-CO_2 pollutants.

Figure 5: Vehicle platooning by SCANIA.[5]

Different studies and on-road trials have been conducted to validate the effectiveness of platooning. In the Partners in Advance Transportation Technology (PATH) project, researchers conducted platooning on heavy-duty vehicles. It showed fuel-saving about 11% at 3-4 meters spacing to about 8% at 8-10 meters spacing of vehicles (Browand, McArthur, and Radovich, 2004). More recent tests shown approximately 10% fuel saving for the inter-vehicular distance of 10 meters (Alam, Gattami, and Johansson, 2010; Bonnet and Fritz, 2000; Lammert et al., 2014). Turri, Besselink, and Johansson proposed a controller to save up to 12% of fuel for following vehicles compared to existing platoon controllers and to safely react to emergency braking of the leading vehicle (Turri, Besselink, and Johansson, 2016). Most of the platooning test runs are conducted in controlled environments, without the interference of external traffic. The KONVOI project conducted a test run of a four-heavy-duty-vehicle platoon on a public highway, but no fuel benefit is observed due to traffic interference (Wille, Röwenstrunk, and Debus, 2007). In another test run on a public highway, 5% fuel saving is observed for three-vehicle platoon (Alam et al., 2015).

In vehicle platooning, automation is used to control a vehicle's longitudinal movement. It helps to maintain a short inter-vehicular distance that is not possible to maintain by human drivers. The automatic control of the longitudinal dynamics can largely reduce the chance of collision. Researchers calculated the safety intra-platoon distance (Chien and Ioannou, 1992; Doi et al., 1994; Fujita, Akuzawa, and Sato, 1995; Seiler, Song, and Hedrick, 1998) to avoid collisions. In the occurrence of any unexpected event such as an accident or a vehicle cuts-in, the platooning vehicles can react promptly by decelerating at maximum without causing collision among themselves. The

5 Transport Topics, https://www.ttnews.com/articles/developers-seek-advance-truck-platooning-through-higher-automation-global-demonstrations, accessed July 14, 2019

PATH project addressed the safety issue during platoon operations (Alvarez and Horowitz, 1999; Li, Alvarez, and Horowitz, 1997). Control laws for safe merging and splitting maneuvers and the safe state set for CACC frameworks are also proposed (Alam, 2014; Li, Alvarez, and Horowitz, 1997). Nunen et al. addressed the safety issues due to connectivity loss during platoon maneuvers (Nunen et al., 2017).

Other than the fuel advantage, emission control, and safety measures, the coordination and control strategies of a platoon make better utilization of space, and hence, increase road capacity and throughput. Michael et al. have shown vehicle platooning has the potential to significantly increase the highway capacity (Michael et al., 1998).

So, the vehicle platooning addresses the major challenges of transportation sector related to congestion, cost of fuel, environmental issues along with the other problems, such as driver shortage and retention, driver wellness and health, hours of service, insurance cost, government regulations. Platooning addressed these challenges by offering improved road safety, energy and emission savings, smoothening traffic flow, optimizing supply-chain management, routing and planning, using alternative fuel or hybrid vehicles. Also, platooning can be adopted and integrated with emerging solutions such as intermodal transportation and green logistics because it only affects the way trucks ply on the road. This makes platooning attractive and important for the transportation industry in the long term. Hence, overall the platooning meets a sustainable balance between economic, environmental and social objectives.

1.3 research scope

As vehicle platooning is an emerging area of recent Intelligent Transportation Systems (ITS), there are several scopes of improvement in platoon strategies and platoon behavior. Till to date, literature mainly focused on the control strategies (Gao et al., 2016; Gong, Zhou, and Peeta, 2018; Shladover et al., 2015; Turri, Besselink, and Johansson, 2016), vehicle-to-vehicle communication (Bergenhem, Hedin, and Skarin, 2012; Fernandes and Nunes, 2010; Jia and Ngoduy, 2016; Jia, Ngoduy, and Vu, 2019; Ucar, Ergen, and Ozkasap, 2018), and fuel and safety aspects (Karoui et al., 2017; Liang, Mårtensson, and Johansson, 2015; Turri, 2018; Yang et al., 2018) of a platoon. The conceptualization of platooning objects and their operations remained unattended. Throughout a platoon lifecycle, starting from platoon birth, up to the platoon death, the coordination of the platoon members are required. A platoon member needs to synchronize with other group members while performing certain behaviors and coping with the general traffic around. The literature addressed platooning objects and some platoon operations, but did so mostly in the context of control or communication. The conceptualization of platooning objects and platoon operations are incompatible across the projects or vehicle manufactures. A gap is observed toward an agreed formalization of the platooning objects, the platoon properties, and the platoon operations in particular.

There is also little work done on platoon formation strategies. Some literature explores control and communication aspects of platoon merging (Kita and Yamada, 2019; Paranjothi, Atiquzzaman, and Khan, 2020). Most of the strategies perform platoon formation on a ramp before entering the highway, or at the highway junction area by the vehicles entering the highway from a ramp with vehicles or platoons traveling already on the highway (Dao, Huissoon, and Clark, 2013; Hall and Chin, 2005; Hobert, 2012). In these formation strategies, only tail merge operation is considered, where a free-flow vehicle merges with another free-flow vehicle or with an existing platoon at the end. In realistic scenarios, however, one would expect platoons traveling in traffic could be formed or dissolved in a more customized way on the fly. It is challenging to perform platoon operations in traffic on the highway as traffic may impact the platooning operations. Moreover, more than one vehicle from traffic can express the merge request. Here, the challenge is to select the proper merging vehicle that assures merge success and less operational time. Also, a requesting vehicle can express a merge request when approaching the platoon on the highway from the back, front or the side of the platoon. In those cases, allowing merge operations only at back may not be efficient. The tail merge could be impeded or fail due to the traffic. This expectation leads to a need for a more flexible choice of merging operations, and results to unknown impacts of such behavior on traffic. This shows that there is clear research need to explore all possible merge operations for platoon formation strategies. There is also a scope of analyzing the impact of platoon operations on traffic, and vice-versa of traffic on platoon operations.

The current literature and on-road platooning trials typically assume a planned formation and decomposition of platoons, mostly at source and destination. In contrast, this research considers platoons that can be formed in an ad-hoc manner, that is on the fly and opportunistically. The question arises whether the original benefits of platooning can be preserved for the ad-hoc formations. The fuel advantage of platooning may not be realized if a platoon has to perform frequently merge and split operations, or if the members join the platoon for a short time only. In these cases, the benefits of platooning may not amortize the costs of forming a platoon. Hence, out of all possible opportunities of platoon generation in traffic, only some could be beneficial. Therefore, it is crucial to decide whether or not to platoon in a given traffic situation. Also, there could be multiple possibilities of platoon formations at any time. A multi-lane highway provides scope for a lane change, speed adjustment and rearrangement of vehicles. Therefore, platoons can be formed in many different ways: based on the destination order, with a destination range constraint, or randomly. The benefits of these different strategies may also differ. Therefore, the scope is to analyze ad-hoc platoon formation and dissolution strategies and their corresponding benefit of forming platoons.

1.4 RESEARCH CHALLENGES

The background study and existing research gaps motivate to address the following research challenges.

- *Conceptualization of platooning objects, platoon properties, and platoon operations.* As there does not exist any agreed platoon concepts, specifically, platooning objects, platoon properties, and platoon operations, it is challenging to define them to support the coordination-based movement. It requires to define basic platoon operations and the derived complex operations that a platoon should perform to handle different traffic scenarios.
- *Modeling and implementation of the front merge, middle merge and tail merge operations and analyzing their impact.* The challenge is to model and implement different platoon formation operations with the help of the defined platooning concepts. It requires to analyze different merge operations to understand the impacts on the traffic and the traffic's impacts on the merge operations.
- *Building a decision model that recommends a strategy of platooning vehicle selection to form fuel-efficient platoons.* In traffic, there could be many possibilities of platoon formations from any number of given vehicles. Some of the formation attempts may not succeed. A failed attempt comes with costs of higher fuel consumption than traveling without the platoon attempt. Thus, it is important to decide a priori which vehicles could try to form platoons and which vehicles should better travel independently. As there are many possibilities for allocating vehicles to platoon groups, it is not feasible to analyze the cost-benefit ratios for all possible combinations in order to find the optimal one. It requires to build a decision model to recommend vehicles and a strategy of fuel-efficient platoon formation.
- *Modeling and implementation of ad-hoc platoon formation and dissolution strategies.* This research considers ad-hoc platoon formation and dissolution strategies. The strategies have some benefits and some drawbacks. Thus, it requires to implement and evaluate the strategies in a simulation environment to determine which strategy outperforms in a given traffic scenario.

1.5 SIGNIFICANCE OF THE STUDY

The research aims to contribute in the following areas as shown in Figure 6.

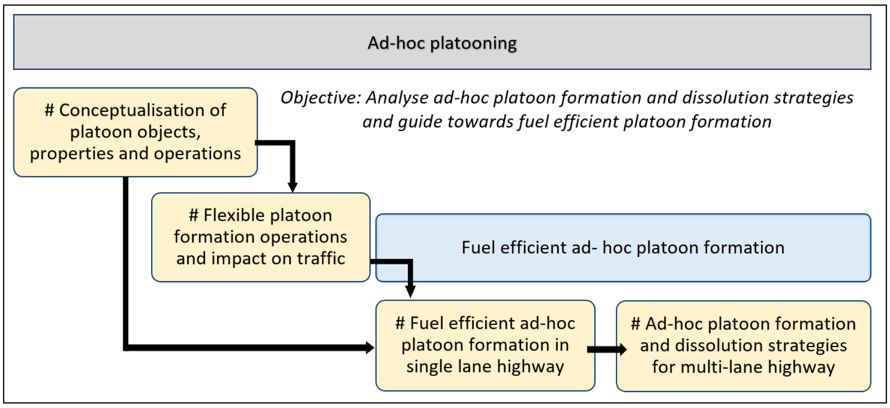


Figure 6: Research framework.

- In order to address the first research challenge, this research proposes platoon ontology that conceptualize the platooning objects and platoon properties, and platoon operations in order to standardize them. The research demonstrates how objects, properties, and operations interact to enable any complex behavior of platoon.
- To address the second research challenge, this research models and implements different platoon merge operations and scenarios in a simulation platform. This research analyzes the merge 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.
- To address the third research challenge, a clustering and classification based platooning vehicle selection model is proposed. Here, the success rate of identifying fuel-efficient platoons validates the proposed selection model. This research demonstrates and validates a real-time decision model that guides to generate and maintain platoons in a fuel-efficient way.
- To address the fourth research challenge, this research analyzes the fuel efficiency of the ad-hoc platoon formation and dissolution strategies on a multi-lane highway. This part of research contributes towards identifying fuel-efficient platoon formation and dissolution strategy in a given traffic situation.

1.6 ORGANIZATION OF THE THESIS

This thesis contains nine chapters, including this introductory chapter. This chapter explains the background and the motivation of the work, identifies potential research challenges, and the contribution related to the research goals.

Chapter 2 - Literature Review: This chapter provides the state of the art of the related research areas. The first part explores different platooning projects to identify the platooning objects, platoon properties, and platoon operations referred to the literature. The next part provides an overview of different platoon formation techniques, their pros and cons. The third part presents different simulation environments related to vehicle platooning used in literature.

Chapter 3 - Conceptualization of vehicle platoons and platoon operations: In this chapter, the work on the conceptualization of platooning objects, platoon properties and abstraction of platoon operations are presented in detail. The platooning concepts are illustrated with examples, and the discussion provides the comparison of platooning concepts of literature and the proposed concepts.

Chapter 4 - Modeling: This chapter explains the modeling blocks that play an essential role in the proposed simulation. It is the platform for the following chapters. It explains the car-following model, lane change model, fuel model, and the network model and their use in the simulation environment.

Chapter 5 - The impact of flexible platoon formation operations: This chapter models and implements platoon formation based on three merge operations, namely *front*, *middle* and *tail* merge operations. This part of research analyzes and compares the merge operations based on their impact on traffic and the traffic's impact on the operations.

Chapter 6 - Fuel efficient ad-hoc platoon formation on a single-lane highway: This chapter provides the methodology of the platooning vehicle selection and a decision model to guide towards fuel-efficient platoon formation in a single lane highway. The efficiency of the proposed model is supported by the real-time use of the decision model and experimental results.

Chapter 7 - Ad-hoc platoon formation and dissolution strategies on a multi-lane highway: Two different ways of ad-hoc platoon formation and dissolution strategies in the multi-lane highway are presented in this chapter. The comparison of the formation strategies based on platoon fuel efficiency is presented along with the experiments and experimental results.

Chapter 8 - Discussion: This chapter describes the overall contributions with respect to the research challenges and the limitations of the research work.

Chapter 9 - Conclusion: The concluding chapter provides a summary of our research work. It also highlights potential future research directions.

2 LITERATURE REVIEW

This literature review surveys a growing body of research concerned with different aspects of vehicle platooning. The chapter commences with a review of the concepts of platooning objects, platoon properties, and platoon operations referred to the different platooning projects. It follows a review of the use of *ontology* in the area of intelligent vehicles. This research aims to analyze different platoon formation and dissolution strategies in a simulation environment. The next part of the literature survey provides a detailed description of platoon formation strategies, on-road trials and their pros and cons. The third part of the survey presents the simulation environments referred to the literature.

2.1 PLATOONING CONCEPTS

In the last few decades, several platooning projects explored vehicle platooning with different aims. These projects defined platooning objects, platoon properties, and platoon operations as per their own notion. The following section presents a brief summary of these platooning projects, corresponding platooning properties, operations, and project objectives.

1. *SARTRE* - A European platooning project Safe Road Trains for the Environment (SARTRE), had the objectives of energy saving, congestion control, enhancement of safety, and driver convenience and comfort. In this project, a platoon is defined as a collection of vehicles with one manually controlled lead vehicle and one or more autonomously controlled follower vehicles. SARTRE allowed heterogeneity in vehicle type and aimed to realize platooning without any change of road infrastructure. The project assumed automation in both lateral and longitudinal control. In SARTRE, the vehicles are defined as *following vehicle*, *lead vehicle*, *other vehicle*, *potential following vehicle*, *potential lead vehicle*, *potential platoon vehicle*, or *platoon vehicle*. Different platoon operations such as *create platoon*, *join platoon*, *maintain platoon*, *leave platoon*, and *dissolve platoon* are defined as platoon use cases (Bergenhem et al., 2010; Robinson, Chan, and Coelingh, 2010).

2. *PATH* - The US-based truck platooning project PATH aimed to enhance the road capacity, safety and to reduce fuel consumption through platooning. In this project, the vehicles used for

platooning are fully automated in lateral and longitudinal control. While maneuvers like lane keeping or longitudinal spacing control can be performed by a single controller independently, coordination is required for entry and exit maneuvers (Rajamani et al., 2000). PATH referred only two types of platoon objects *lead vehicle* and *preceding vehicle* and platoon properties such as inter-vehicle spacing, inter-platoon spacing, platooning vehicle types, number of vehicles in the platoon, platoon length, vehicle acceleration or deceleration, communication time lag and delay, and highway operating speed (Carbaugh, Godbole, and Sengupta, 1998; Michael et al., 1998; Rajamani et al., 2000). Operations like *lane keeping, lane change, join,* and *split* are tested in this project.

3. *SCANIA* - The Swedish truck maker SCANIA launched two platooning projects: Distributed Control of a Heavy-Duty Vehicle Platoon, and iQFleet (Bergenhem et al., 2012) with the primary objective of fuel-saving. Here, only longitudinal movement is automated. Unlike other projects, the controlling mechanism is distributed, which implies that each vehicle is responsible for its own control based on information from the on-board sensors (e.g., radar, cameras) and information exchange via vehicle-to-vehicle communication. In iQFleet, the research is focused on platoon control with respect to road topology and infrastructure. In these projects, Deng modeled a platoon class as a group of heavy-duty vehicles with platooning capability and having three mandatory properties: *platoonID*, *speed* and a list of platoon members (Deng, 2016). The driving behavior of a platoon is classified into basic and advanced operations. Basic operations include *acceleration, deceleration and desired inter-vehicle distance adjustment*. In contrast, *speed planning and platoon aggregation and disaggregation* are considered advanced operations.

4. *Others* - Also, the Japanese platooning project Energy ITS aimed at energy saving and driver support (Tsugawa, Kato, and Aoki, 2011). The vehicles used in the platoon are fully automated and follow a dedicated lane during movement. In ITS, Tsugawa, Kato, and Aoki defined the control system for path following and lane keeping operations. European platooning project CHAUFFEUR analyzed potential fault conditions and the communication protocol during coupling (Fritz et al., 2004). CHAUFFEUR demonstrated different maneuvers such as, *coupling*, termed as 'flying joint', *de-coupling*, termed as 'inverted flying joint', and others like *lane changing, accelerating and braking*. German platooning project KONVOI aimed at traffic flow improvement and also analyzed fuel saving with respect to the

intra-platoon gap (Wille, Röwenstrunk, and Debus, 2007). The platoon was tested in real traffic.

To encourage development, integration and deployment of co-operative driving the Grand Cooperative Driving Challenge has been organized 2011 and 2016 (Englund et al., 2016). The challenge focused on platooning based on vehicle-to-vehicle and vehicle-to-infrastructure communication, and established data fusion and control technologies. In this challenge, coordination between vehicles is achieved by sharing the surrounding vehicles' state and road information to automatically control a vehicle's longitudinal motion. In terms of platoon operations, the challenge mainly tested collaborative vehicle movement as a platoon based on predetermined technology and interoperable communication standards and tested a *join* operation and allowed the change of role of participating vehicles (Bergenhem et al., 2012; Lidström et al., 2011).

In recent years, the European commission initiated ENSEMBLE (ENabling SafE Multi-Brand pLatooning for Europe) project (Konstantinopoulou, Coda, and Schmidt, 2019). that develops specifications for multi-brand truck platooning to demonstrate platooning of six different truck OEMs. The project described the functional architecture, captures all minimum set of operations layer requirements and tactical layer specifications for the basic level of platooning. The building blocks of truck platooning consists of in-vehicle requirements (Longitudinal, sensors, HMI interaction), infrastructure (V2I), information among trucks in a platoon, and platooning strategy (coordination mode, gap regulation, formation, dissolution, and vehicle mix). The plan is to implement and demonstrate all the functionalities in 2021.

Other than the above mentioned platooning projects, Amoozadeh et al. presented a platoon management protocol and simulated three basic platoon maneuvers: *merge*, *split*, and *lane change* (Amoozadeh et al., 2015). They also explained three platooning scenarios: leaving of the leader, leaving of a follower, and entry at the end. The platoon management protocol considered five different variables that any platoon enabled vehicle should have, namely *vehicle ID*, *platoon ID*, *platoon depth*, *platoon size* and *platoon members*.

Though different research projects and research articles discussed some of the platoon maneuvers and platoon properties, none of them defined those operations formally. More precisely, the different projects defined platooning objects and platoon operations in incompatible ways. For example, the *join* operation in SARTRE is the same as the *aggregation* operation in SCANIA's projects, and the *coupling* operation in CHAUFFEUR. Not only the terminology differs, but also the object and operation concepts. SARTRE used eight different platooning objects to address different platoon operations whereas most of the other projects used three objects: *platoon leader*, *platoon follower*, and *platoon*, and sometimes additionally the concept of *free vehicle*. SCANIA's projects defined the platoon creation and the platoon join separately, whereas other projects did not address platoon creation or considered *create* as an implicit operation of *join*. Moreover, typically no justification and explanation have been provided on the operation categorizations. Therefore, it is clear that standardization of platooning objects, properties and platoon operations is missing which is necessary to coordinate and cooperate across the platoons of vehicles of various manufacturer.

2.2 ONTOLOGY IN INTELLIGENT TRANSPORTATION SYSTEM

In computer science and information science, an ontology encompasses a representation, formal naming and definition of the categories, properties and relations between the concepts, data and entities that substantiate one, many or all domains of discourse. An ontology provides the potential terms to describe knowledge of a particular domain or subject matter. More precisely, an ontology is not a domain vocabulary but the conceptualizations that the terms in the vocabulary are intended to capture (Chandrasekaran, Josephson, and Benjamins, 1999; Guarino, 1998). In ITS, ontology is used for different objectives, such as for managing and sharing the knowledge between vehicles (Feld and Müller, 2011), for developing a model for assisted driving and interaction (Boudra et al., 2015), for determining the automation level of an automated vehicle (Pollard, Morignot, and Nashashibi, 2013), and for the communication between situation-aware vehicles (Choi, 2015). The main motivation of using an ontology is to agree on a common understanding of entities in the proposed model to support interoperability, i.e., the interaction between diverse agents.

The model proposed in (Feld and Müller, 2011) requires semantic knowledge about the user, the vehicle, the driving situation, and interaction between them. Here, ontology is used to obtain a common understanding of knowledge. Boudra et al. considered the traffic situation, traffic rules, and the context of the driver, the vehicle, and the environment in order to prevent an accident (Boudra et al., 2015). This research used the ontology to represent a driving model and the road environment. Pollard, Morignot, and Nashashibi defined a spectrum of automation layers from fully manual to fully automated vehicle, based on ontology-based knowledge representation (Pollard, Morignot, and Nashashibi, 2013). Choi conceptualized the vehicle-to-vehicle communication standards mainly for an emergency context using an ontology (Choi, 2015). The research defined the ontology in three different levels: domain level, task level, and application level to support inter-vehicle interaction, context update, and a vehicle decision-making process. Similarly, this research aims to standardize the concepts of platooning. Therefore, platooning is conceptualized with the help of an ontology.

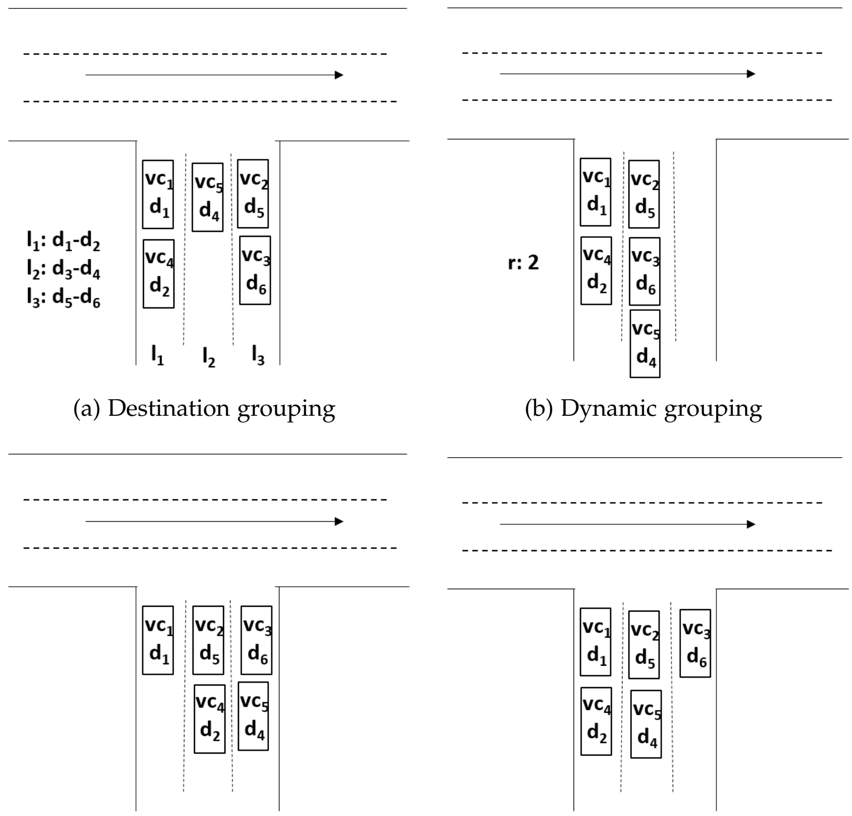
2.3 PLATOON FORMATION STRATEGIES

Different projects presented platoon behaviors based on their own defined concepts. Among all, platoon formation and dissolution are two important platoon behaviors. 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.

2.3.1 *Ramp-based Formation*

In ramp-based formations (Hall and Chin, 2005), 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. The ramp-based formation strategies are shown in Figure 7. Let us assume there are three lanes on the ramp, - l_1, l_2, l_3, and six destinations, d_1 to d_6. Here, d_1 is the nearest destination and d_6 is the farthest destination. Also let us assume that five vehicles vc_1 to vc_5 arrive with destinations d_1, d_5, d_6, d_2, and d_4.

1. *Destination grouping*: In this strategy, the lanes of the entrance ramp are preassigned for some destinations. Hence upon arrival, vehicles are statically assigned to the pre-assigned lanes. Figure 7a shows the destination grouping. In this example, l_1, l_2, l_3 are assigned for the vehicles of destinations d_1 to d_2, d_3 to d_4 and d_5 to d_6, respectively. Hence, as per destination group strategy, vc_1 and vc_4 of destinations d_1 and d_2 are assigned to l_1, vc_5 of destination d_4 is assigned to l_2 and vc_2, vc_3 of destinations d_5 and d_6 are assigned to l_3. Once any of the termination conditions is satisfied, a lane is released and the corresponding vehicles make a single platoon. The destination group formation strategy may cause longer waiting time for vehicles and result in smaller platoon size on average. This strategy does not guarantee equal division of the vehicles in all lanes. It leads to a possibility that the vehicle queue in one lane is long and other lanes are empty.



(a) Destination grouping

(b) Dynamic grouping

(c) Dynamic grouping and platoon splitting

(d) Random formation

Figure 7: Ramp-based formation strategies.

2. *Dynamic grouping*: In dynamic grouping, only the value of the destination range r 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. It is possible that a vehicle can be a possible candidate for more than one platoon. In that case, the vehicle is assigned to a platoon having most similar destination vehicles. Let us consider the destination range r is 2 and as per the previous example the five vehicles arrive in the same way at the entrance ramp. In this strategy, vc_1 of destination d_1 is first assigned to l_1. Then, vc_2 of destination d_5 arrives. But the difference of the destinations d_1 and d_5 is more than 2. Hence, vc_2 is assigned to l_2. Next, vc_3 of destination d_6 appears, it can not be assigned to l_1 having vehicle vc_1 of destination d_1 but is assigned to l_2 having vehicle vc_2 of destination d_5. Similarly, vc_4 of destination d_2 is assigned to l_1 and vc_5 of destination d_4 is assigned to l_2. Figure 7b illustrates the example of dynamic grouping. As the destination range is fixed in dynamic grouping, the platoon members have similar destinations. Smaller destination range ensures that a platoon travels longer distance without a

split. But with smaller distance range it is difficult to cover all vehicle destinations as the lanes are limited. It complies quicker platoon release leading smaller average platoon size.

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. A vehicle is assigned to a lane if the last assigned vehicle of that lane has a farther or equal destination. If none of the lanes satisfies the ordered condition, one of the lanes has to be released. As per the previous example, the vehicle vc_1 of destination d_1 is assigned to l_1. Next, vc_2 of destination d_5 can not be assigned to l_1 as that will generate a disordered platoon. Therefore, vc_2 is assigned to l_2. Similarly, vc_3 of destination d_6 is assigned to l_3. vc_4 of destination d_2 can not be assigned to l_1, it is assigned to l_2 as the difference between the destinations of $vc_2(d_5)$ and $vc_4(d_2)$ is lesser than the difference between $vc_3(d_6)$ and $vc_4(d_2)$. In similar way, vc_5 of destination d_4 is assigned into lane l_2. Figure 7c depicts the order based platoon formation strategy. In order based formation, a platoon travels as reduced platoon when one or more members leave the platoon upon reaching the destination ramp. This strategy requires less platoon maneuvers, which enhances platoons stability.

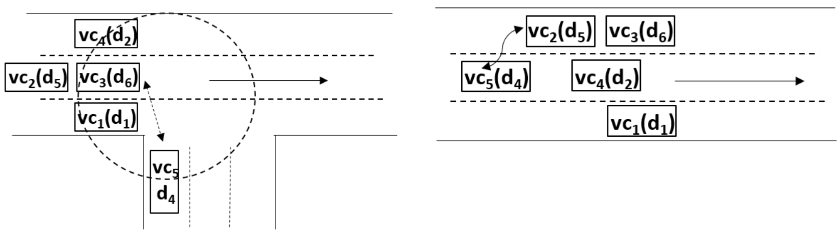
4. *Random formation*: As the name suggests, in this strategy, the vehicles are assigned randomly to all the ramp lanes. Figure 7d shows an example of random platoon formation. In random platoon formation, vehicles can be equally distributed between lanes which increases average platoon length, but as the vehicles are randomly distributed, the destinations of the platoon members may not be in order. Platoon members may leave the platoon from any position upon reaching the destination ramp. Thus, a platoon needs to rebuild. Therefore, during the dissolution, the platoons become unstable.

All the four ramp-based formation strategies demand extra waiting time to form the platoon at the ramp.

2.3.2 *Ramp-highway-based Formation*

The alternative way of formation is ramp-highway-based platoon formation shown in Figure 8.

1. *Optimized platoon formation*: This strategy relies on the optimization of vehicle assignment based on their destination (Dao, Huissoon, and Clark, 2013). In this formation, a vehicle from



(a) Optimized platoon formation (b) Transient formation

Figure 8: Ramp-highway-based formation strategies.

entrance ramp creates a platoon with other ramp vehicles or already existing platoons on the highway. When a vehicle reaches on the entrance of the ramp, it communicates all other vehicles or platoons within the communication range. The logical assignment of a vehicle is done on the ramp, whereas the physical assignment takes place on the highway. If a vehicle fails to find any feasible platoon, it starts a new one. As the merging vehicles do not wait on the ramp for other ramp vehicles to form a platoon, the platoon formation time is less. Figure 8a shows this formation strategy. In the simulation, Dao, Huissoon, and Clark have shown optimized platoon formation strategy increases lane capacity by varying parameters like traffic flow, destination range (Dao, Huissoon, and Clark, 2013). But, the simulation result is not compared with other formation strategies. This research has also shown the tradeoffs between average platoon length and platoon stability.

2. *Transient platoon formation*: In transient platoon formation (Hobert, 2012), a temporary assignment of a vehicle to a non-feasible platoon is allowed in the absence of a feasible platoon. In this strategy, a vehicle enters in the highway as an individual vehicle and starts looking for a feasible platoon. A vehicle is allowed to join a platoon if its destination is closer and nearer than the platoon leader's destination. If no feasible vehicle or platoon is found, the vehicle is temporarily assigned to a closest non-feasible platoon and continues searching. If a feasible platoon is found later, the vehicle leaves the non-feasible platoon and joins to the feasible one. Hence, a vehicle never travels alone. This strategy increases the average platoon size. But the temporary assignment compromises platoon stability.

In all these strategies, the formations are done in a planned way and only tail merge operation is performed during the formation. The planned ways of formations are not suitable when the platoons are formed on the fly. On the fly, the upcoming platoon members can be selected from the vehicle candidate list. The selection can be made by the platoon leader based on the criteria such as the distance of the vehicle from the platoon, traffic density around the vehicle, vehicle's traveling distance. In such on the fly or ad-hoc formation, the vehicles need to catch up one another to form a platoon. To support this ad-hoc formation, flexible merge operations are desirable as a platoon member can approach from the back, the front, or the side of the platoon (Maiti, Winter, and Kulik, 2017; Rahman and Abdel-Aty, 2018). This ad-hoc platoon formation with the help of flexible operations is not analyzed in the above-mentioned formation strategies.

Apart from the mentioned platoon formation strategies, Liang proposed a mathematical model to decide when it is fuel-efficient to catch up with a platoon for a heavy-duty vehicle (Liang, 2016). The model does not consider acceleration and deceleration of vehicles, assuming the fuel costs are negligible for travels over long distances. However, in ad-hoc platooning scenarios, travel distances ahead do not need to be long, and thus, fuel consumption during the platooning operation can matter. Hoef, Johansson, and Dimarogonas presented an approach to extract features and rules out a majority of possible pairs of vehicles to form platoons (Hoef, Johansson, and Dimarogonas, 2016). Then the algorithm decides if platooning is possible for a pair based on the complete data associated with the pair of vehicles. However, this work not referred any strategy of platoon formation.

Meisen, Seidl, and Henning used data-mining techniques to mine frequent sub-routes to plan and organize a platoon formation (Meisen, Seidl, and Henning, 2008). Larson, Liang, and Johansson used controllers at the junctions of the road network to coordinate and reroute vehicles to form a platoon in a fuel-efficient way (Larson, Liang, and Johansson, 2015). Larsson, Sennton, and Larson proposed an optimal fuel solution for the platoon routing problem. In this work, a mathematical framework is used to model trucks traveling in road networks. This work presents integer linear programming formulations for instances of the platoon routing problem where deadlines are discarded. It allows calculating fuel-optimal solutions to the platoon routing problem for large-scale, real-world examples (Larsson, Sennton, and Larson, 2015). Nourmohammadzadeh and Hartmann used the genetic algorithm and proposed a mathematical model for the fuel-efficient platooning problem with a deadline for each vehicle (truck) to reach its destination (Nourmohammadzadeh and Hartmann, 2016). In contrast to all these strategies, our proposed methodology analyzes ad-hoc platooning, that includes platooning vehicles selection from free-flow traffic, performing flexible platoon operations, platoon formation, travel and platoon decomposition on multi-lane highways. The experimental results provide an analysis of fuel benefit that helps to select the formation strategy in a given traffic situation.

2.4 SIMULATION ENVIRONMENT

The existing traffic simulators such as Microscopic Traffic Simulator (MITSIM) (Yang and Koutsopoulos, 1996), Multi-Agent Transport Simulation (MATSIM) (Horni, Nagel, and Axhausen, 2016), Simulation of Urban Mobility (SUMO) (Fernandes and Nunes, 2010), Transportation Analysis and Simulation (TRANSIMS) (Smith, Beckman, and Baggerly, 1995), PARAMICS (Cameron and Duncan, 1996), AIMSUN,(Barceló and Casas, 2005) CORSIM (Halati, Lieu, and Walker, 1997), CARSIM (Benekohal and Treiterer, 1988), and Verkehr In Städten Simulations Model (VISSIM) (Fellendorf and Vortisch, 2010) have all been used to study, analyze and predict the traffic behavior (Fernandes and Nunes, 2010). Among them, MITSIM, MATSIM, SUMO, and TRANSIMS are open source. Most of the simulators model human driving behavior and intelligent driving models to analyze the scenarios under different conditions. In traffic simulation models, direct short-range communication is used to support inter-vehicle communication.

MATSIM is an open-source framework for implementing large-scale agent-based transport simulations. The framework consists of several modules which can be combined or used stand-alone. MATSIM offers a framework for demand-modeling, agent-based mobility-simulation, re-planning, a controller to iteratively run simulations as well as methods to analyze the output generated by the modules. MITSIM was developed for modeling traffic networks with advanced traffic control, route guidance and surveillance systems. MITSIM represents networks in detail and simulates individual vehicle movements using car following, lane changing, and traffic signal responding logic. SUMO is an open-source, highly portable, microscopic and continuous traffic simulation package designed to handle large road networks. SUMO is developed based on the Gibbs-Model extension and intelligent driving model. TRANSIMS is an integrated set of tools to conduct regional transportation system analyses based on a cellular automata microsimulator. It models individual travelers and their multi-modal transportation based on synthetic populations and their activities. Compared to other transportation aggregate models, TRANSIMS represents time consistently and continuously, as well as detailed persons and households. Its time-dependent routing and person-based microsimulator also differ from other aggregate models. PARAMICS microsimulation is the traffic modelling software to enable transport professionals to design, evaluate and present simulations. Traffic simulator AIMSUN provides software and services for traffic planning, simulation and prediction. CORSIM microscopic traffic simulator includes both NETSIM for surface street simulation and FRESIM for freeway simulation. CARSIM is a commercial software package that delivers methods for simulating the performance of passenger vehicles and light-duty trucks. CARSIM predicts the performance of vehicles in response to driver controls such as steering, throttle, brakes, clutch, and shifting in a given environment of road geometry, coefficients of friction, wind. PTV VISSIM is a microscopic multi-modal traffic flow simulation software package that offers traffic analysis and forecasting. It is also used for signal optimization and analyzing the traffic impact.

platoon formation strategies have been mainly evaluated in the VISSIM simulation platform (Fellendorf and Vortisch, 2001). Amoozadeh et al. tested the platooning scenarios in the integrated simulation platform Vehicular Network Open Simulator (VENTOS) combination of SUMO and OMNET++ (Amoozadeh et al., 2015). Also, Platooning Extension of VEINS (PLEXE) (Sommer, German, and Dressler, 2011), has been used in the literature for simulation. It runs experiments in realistic scenarios, taking into account physics and mechanics of the vehicles, communications and networking impairments, and the Inter-Vehicle Communication protocol stacks (Segata et al., 2014). This research aims to analyze the platoon's behavior, such as analyzing platoon operations, the ad-hoc formation and dissolution of a platoon, the impacts of platooning on traffic and vice-versa. Hence, the requirement is to select a microscopic simulator the offers to design the network for simulation and to control the vehicles throughout the simulation to perform platoon operations. As this research deals only with operation level analysis, not the V2V communication details, a simple traffic simulator is good to perform the experiments under consideration.

This research selects SUMO traffic simulator as it is open source and supported by detailed documentation. It is under the GNU General Public License (GPL), compatible for both Windows and Linux platforms. As an extension, Traffic and Network Simulation Environment (TraNS) has been proposed to integrate SUMO and vehicular network simulator. Similarly, Traffic Control Interface (TraCI) has been proposed to integrate SUMO with other applications such as Matrix Laboratory (MATLAB), PYTHON using Transmission Control Protocol (TCP)-based client-server architecture. With the help of TraCI, the external applications can control vehicle parameters on run time. TraCI allows to feed attribute values of vehicles, traffic lights, induction loops, road infrastructure, and other simulation objects. It also allows to retrieve values of the simulation objects and to act based on that. This extension is helpful for platooning purpose to control vehicles externally on run-time. In this research, SUMO is used as the simulation platform and MATLAB is used as the external controller. A graphical Network Editor (NETEDIT) of SUMO provides a GUI to create and modify the road network is also used for simulation.

3 CONCEPTUALIZATION OF VEHICLE PLATOONS AND PLATOON OPERATIONS

The core of this chapter has been published as Maiti, S., Winter, S. and Kulik, L. (2017). A Conceptualization of Vehicle Platoons and Platoon Operations. In: *Transportation Research Part C: Emerging Technologies*, 80, pp.1-19. Santa Maiti did this research under the supervision of the co-authors.

The background study and the literature review in the previous chapters have already established the requirement of a 'common language' and an agreement on platoon protocols to perform operations and to form platoons in an ad-hoc manner. This chapter aims to fill this fundamental gap by developing a formal model of platooning concepts. For this purpose, different platooning objects, platoon operations, and platoon properties are collected from different platooning projects. Platoon operations are analyzed in order to find the minimal set that is necessary and sufficient to represent all platoon behaviors. Next, the operations are abstracted at three different levels. The base level of abstraction is identified as atomic functions. Further decomposition of an atomic function is not required. The next level of abstraction is identified as the primitive operation that is composed of only atomic functions. And the highest level of abstraction is the derived operation that is the aggregation of one or more primitive operations and atomic functions, or by recursive use of a single primitive operation.To represent the platoon concepts, properties and to abstract platoon operation in a standard way, ontology has been used. The ontological model is implemented and demonstrated.

3.1 INTRODUCTION

The literature addresses platooning objects and some platoon operations but does so mostly in the context of control, communication or simulation. It shows that there is clear research need towards an agreed formalization of the platooning objects, the platoon properties, and the platoon operations. Only with an agreed formalization vehicles of various manufacturers can coordinate and deal with complex traffic scenarios. Throughout a platoon lifecycle, starting from platoon formation up to the platoon dissolution, the coordination requires from each platoon member to apply certain behavior in order to synchronize with other group members as well as to cope with the general traffic around. Each platoon maneuver needs to be executed in an a priori agreed manner, and yet depends on the individual platoon members' status and properties. Therefore, this research sets out to identify and analyze a set of platoon operations, platoon properties and individual member properties, and the dependency of platoon operations based on predefined platoon rules. The objective of this work is to describe formally platooning objects, platoon properties and basic blocks of platoon operations in order to contribute an agreed understanding at a conceptual level.

Thus, the research challenges addressed are:

1. *Formalization of platooning objects* - A formal approach to distinguish a platoon from other forms of coordinated autonomous driving behavior, such as car-following (Brackstone and McDonald, 1999; Newell, 2002).

2. *Defining platoon properties* - Platoon properties need to be classified into two different levels. The lower level defines properties of individual members whereas the higher level defines properties of a platoon as a whole. A platoon leader's decisions and the corresponding platoon operations depend on both higher and lower level property values. Since this research focuses on the operation, not the control mechanisms of platoons, only operation related properties are specified. Platoon control related properties are out of the scope of this research.

3. *Identification and abstraction of platoon operations* - The basic blocks of platoon operations need to be identified that would be sufficient for a platoon to handle any complex traffic behavior. In general, the identification of basic operational blocks can be done by analyzing different traffic scenarios that a platoon can experience, the interaction of platoon with the rest of the traffic, and the issues the other traffic can face caused by a platoon. While abstracting the platoon operations, the validation of rules, the information updating, and the information synchronization need to be taken care of. This research aims to identify and abstract the basic operation blocks which can define all other complex platoon behaviors referred in the literature. The complex platoon behaviors can be treated as derived operations or higher level operations. Point to note, this research avoids the communication level or control level detailing such as specification of communication protocol or parameter values which can be implementation specific. Planning and optimization of the platoon operations are beyond the scope of this research.

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

1. the conceptualization of platooning objects and platoon properties;

2. the identification and abstraction of platoon operations; and

3. a demonstration of how objects, properties, and operations interact to enable any complex behavior.

Hypothesis: Any behavior of platoons refereed in the existing research literature can be represented as a combination of basic blocks of platoon operations.

In order to support the hypothesis, this research proposed the basic block, a small set of atomic functions and identified the higher level operations. The research starts an inductive proof by showing platoon operations in terms of the basic building blocks. The claim is assumed to be true unless a complex behavior can be found that cannot be represented by the basic blocks.

This chapter is organized as follows. Section 3.2 introduces the formal representation of platooning objects and platoon operations, and Section 3.3 demonstrates the flow of a more complex operation in a given scenario. In order to demonstrate the completeness of the specifications, Section 3.4 maps these objects and operations to the platooning concepts mentioned in the literature. Section 3.5 summarizes the paper.

3.2 CONCEPTUAL FRAMEWORK

Web Ontology Language Description Logic (OWL DL) provides maximum expressiveness in knowledge representation.[1] Additionally, it is computational complete and decidable for reasoning. In this work, OWL DL (Baader, Horrocks, and Sattler, 2004; Krötzsch, Simancik, and Horrocks, 2012) has been used to semantically formalize platooning objects or classes and properties, and to define their interrelationships. Description Logic (DL) syntax is used to describe an OWL ontology, acknowledging minor terminological differences between OWL and DL: *concept* in DL refers to *class* in OWL, and *role* in DL refers to *property* in OWL. A concept (class) is defined with the help of other concepts, linked via roles (properties) and operators. In this work, to represent the ontology using OWL DL, the following operators are used:

1. *concept inclusion* '$\sqsubseteq$' implies subsumption,

2. *concept constructors intersection* '$\cap$' implies conjunction of concepts or roles,

3. *universal restrictions* '$\forall$' restricts role and corresponding concept,

4. *qualified number restrictions* '$\geqslant$' represents minimum cardinality or at-least restriction and to represent exact cardinality '$\geqslant$', '$\leqslant$' are used together.

Figure 9 presents the proposed platooning ontology.

1 www.w3.org/TR/owl-features, accessed April, 2020

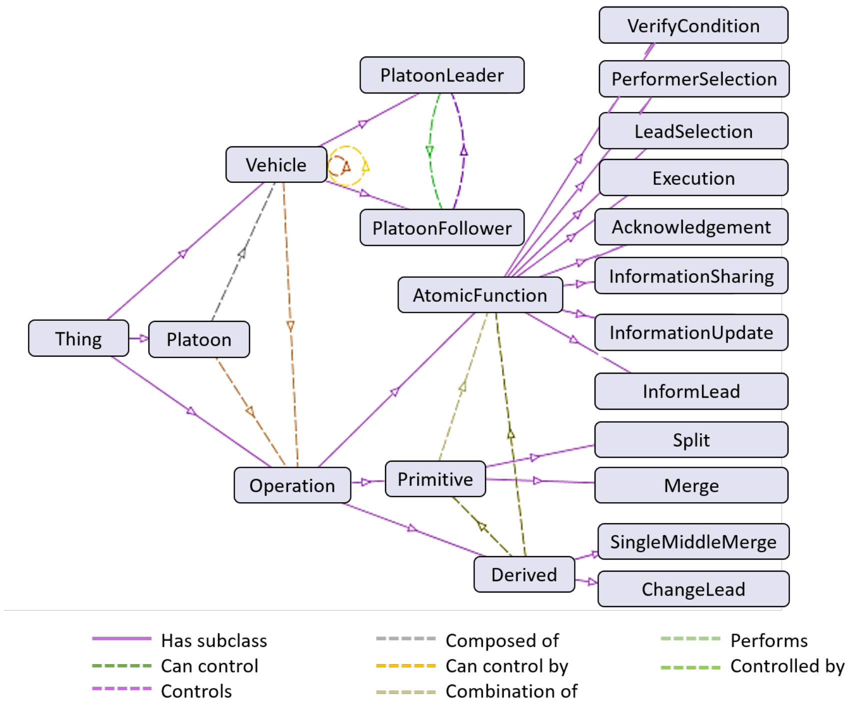


Figure 9: Proposed platooning ontology.

The proposed platooning ontology has three upper classes – a *Platoon* that represents a platoon as an individual entity, a *Vehicle* that is a unit of a platoon or a platoon member and platoon *Operation*, that a platoon or a vehicle performs and a number of subclasses. The object property describes the relation between any two classes. The basic building block of a platoon is a vehicle that can be a platoon leader or a platoon follower. The *PlatoonLeader* and *PlatoonFollower* classes are specializations of *Vehicle* class. *PlatoonLeader* and *PlatoonFollower* are related by inverse object property control. *PlatoonLeader* controls the *PlatoonFollower* and the *PlatoonFollower* is controlled by *PlatoonLeader*. Both, *Platoon* and *Vehicle* can perform platoon operations. Platoon *Operation* class has three subclasses *AtomicFunction*, *Primitive* operation, and *Derived* operation. The *Primitive* operation class is a combination of *AtomicFunction* class and the *Derived* operation class is a combination of *AtomicFunction* and *Primitive* operation classes. This research further discusses eight instances of *AtomicFunction*, two instances of *Primitive* operations, and two instances of *Derived* operations. Along with the object properties, platooning classes are also associated with a number of datatype properties that describe or qualify each class and enable the decision making by a platoon leader. Among all the datatype properties some only belong to *Platoon*, some to *Vehicle*, and others are applicable for both *Platoon* and *Vehicle*. The datatype properties can be static or dynamic based on their frequency of update. If the value of a data property can change within a platoon's lifetime, it is considered a dynamic property e.g., *Location*. Whereas, if the data property value is never updated within a platoon's lifetime e.g., *Capacity* it is considered as a static property. The following section presents the detailed descriptions of individual platooning object classes and corresponding class properties.

3.2.1 *Vehicle*

A vehicle implies a mechanical automobile[2] used as a means of transportation. A vehicle maintains its own information and is capable of maintaining other vehicles' information and can interact with other vehicles. A vehicle may control other vehicle(s) or may be controlled by another vehicle. A vehicle performs operations. Formally,

$$\begin{aligned} \text{Vehicle} \sqsubseteq\ & \text{Automobile} \\ & \cap \text{maintains.Information} \\ & \cap \text{interactsWith.Vehicle} \\ & \cap \text{canControl.Vehicle} \\ & \cap \text{canControlBy.Vehicle} \\ & \cap \text{performs.Operation} \end{aligned} \tag{1}$$

In this representation, *Vehicle*, *Automobile*, *Information*, and *Operation* are classes. *maintains*, *interactsWith*, *canControl*, and *canControlBy* are the object properties of the *Vehicle* class. Information maintained by a vehicle in the knowledge base is the meaningful data about that particular vehicle or other vehicles and described by datatype properties. One or more vehicles can compose a vehicle platoon and can move in coordinated manner. Distinguishing its functionality, the *Vehicle* class is further classified into *PlatoonLeader* and *PlatoonFollower* subclasses. If a vehicle controls other vehicles in a coordinated movement then the vehicle is referred to as platoon leader. A platoon leader not only maintains its own information but also maintains information of its following vehicles. In any platoon, at any given time, there can only be one single leader, but who is the leader can change over time based on the requirement. A platoon leader leads the platoon and makes decisions on behalf of the whole platoon. A vehicle controlled by another vehicle, namely, the platoon leader is referred to as a platoon follower. A platoon follower only maintains its own information and follows the platoon leader's instructions. A single free-flow vehicle that is not in a coordinated movement with any other vehicle has the same properties as a platoon leader and performs the same set of operations. Therefore, a single free vehicle is treated as a special case of a platoon leader: a platoon leader with zero following vehicles. Formally, a *PlatoonLeader* and a *PlatoonFollower* are defined as follows.

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2 www.dbpedia.org/ontology/Automobile, accessed June, 2016

$$\begin{aligned} \text{PlatoonLeader} \sqsubseteq\ & \text{Vehicle} \\ & \sqcap \forall\ \text{controls.PlatoonFollower} \end{aligned} \tag{2}$$

$$\begin{aligned} \text{PlatoonFollower} \sqsubseteq\ & \text{Vehicle} \\ & \sqcap \leqslant 1\ \text{hasLeader.PlatoonLeader} \\ & \sqcap \geqslant 1\ \text{hasLeader.PlatoonLeader} \\ & \sqcap \forall\ \text{controlledBy.PlatoonLeader} \end{aligned} \tag{3}$$

A vehicle is a member of a platoon: either a leader or a follower. Therefore, the *Platoon* class is related to the *Vehicle* class with a *composedOf* relationship. In order to join an existing platoon or to leave a platoon, a vehicle performs merge or split operation. Thus, the *Vehicle* class is linked with the *Operation* class by a `perform` relationship.

The vehicle class as a *PlatoonLeader* or *PlatoonFollower* has the following datatype properties that are used in any platoon's decision-making process.

1. *ID* - the ID is a unique number that identifies a particular vehicle. ID is a mandatory attribute every vehicle must have. The ID has two parts, represented here as PlatoonID-MemberID. The prefix PlatoonID refers to the platoon a vehicle belongs to. All the vehicles belonging the same platoon have the same PlatoonID. The PlatoonID is bound to the lifetime of a platoon. The suffix MemberID is used to identify a member within a platoon. For a vehicle, the PlatoonID may change after performing platoon operations such as *merge* or *split*, while the MemberID stays static.

2. *Role* - The Role of a vehicle can be platoon leader or platoon follower. The role may get updated by platoon operations such as *change lead*. Hence, it is a dynamic property.

3. *Location* - A vehicle's Location property refers to its latitude and longitude. The Location property is dynamic as its value changes continuously over a platoon's lifecycle. The Location property helps a platoon leader in numeric calculations such as the distance from the split point, and thus also helps in decision-making processes such as when to start a maneuver.

4. *Speed* - Speed is a dynamic property of vehicle and a synchronized one in a platoon. Platoon leaders and platoon followers maintain overall the same speed in order to keep a fixed safe distance while traveling in a coordinated manner. Other than during the maneuver operations the relative speed of two platoon members is on average zero.

5. *SpeedLimit* - The SpeedLimit of a vehicle implies the highest speed that the vehicle can achieve. This SpeedLimit constrains the behavior of the platoon not legally, but physically. SpeedLimit depends on different parameters, such as type of vehicle, condition of vehicle, load and load type of vehicle. Hence, a vehicle SpeedLimit is considered as a dynamic property for a vehicle.

6. *Route* - The route of a vehicle is generally fixed during the membership with a platoon unless a detour is decided by the platoon leader. The route is another property used by the platoon leader for decision making processes such as deciding where a vehicle should leave a platoon for their target destinations.

Above mentioned datatype properties are the mandatory ones for specifying the operations of a vehicle in a platooning context. However, the properties can be extended (e.g., remaining fuel, or loading weight) depending on the requirements of individual implementation.

3.2.2 *Platoon*

A *Platoon* is a group of vehicles of minimum group size one. It has exactly one platoon leader and zero or more platoon followers. A platoon can perform different platoon operations. Formally,

$$\begin{aligned} \text{Platoon} \sqsubseteq\ & \text{isComposedOf.Vehicle} \\ & \cap \leqslant 1\ \text{hasLeader.PlatoonLeader} \\ & \cap \geqslant 1\ \text{hasLeader.PlatoonLeader} \\ & \cap \geqslant 0\ \text{hasFollower.PlatoonFollower} \\ & \cap\, \text{performs.Operation} \end{aligned} \tag{4}$$

According to this definition, only the platoon leader is an essential member of a platoon. But a platoon composed of only a platoon leader is a special case of a platoon, referred to as a *degenerated* platoon. A *proper* platoon consists of more than one vehicle, i.e., a platoon leader and one or more platoon followers. A platoon performs different operations, such as merge with another platoon. The interpretation of platoon datatype properties is as follows:

1. *PlatoonID* - The PlatoonID is the prefix part of the vehicle ID. A PlatoonID differentiates a platoon over its lifecycle from other platoons.

2. *Location* - The platoon's Location property refers to its latitude and longitude. As the platoon has a notable length, any platoon's Location property is represented by two vehicle Location properties: the Location of the platoon leader and the location of

the last platoon follower. The location is a constantly changing dynamic property.

3. *Gap* - Two consecutive platoon members maintain an intra-platoon gap within a min-max range based on the control capacity (safe distance) and the intra-platoon communication range. This is a dynamic property, although it remains unchanged unless it is updated by the platoon leader.

4. *SpeedLimit* - A platoon's SpeedLimit property is defined as the minimum of the SpeedLimit value of the individual platoon member's SpeedLimit:

$$\{\min(\max(speed(x)))|\forall x \in P\}$$

   where x is a platoon member and P is a platoon. Since SpeedLimit of a platoon depends on the individual members' speed limits, it gets updated when a new member joins or a member leaves the platoon. This implies, the platoon's SpeedLimit is a dynamic property.

5. *Size* - The size of a platoon is a dynamic property of a platoon and implies the current number of members of the platoon.

6. *Capacity* - This is a static property and defined as maximum how many vehicles are allowed to group together in a platoon.

7. *Lane* - Lane is a dynamic property correlated with the platoon leader's Location. However, it is a *relative* position property, and observed from different sensors than the Location value due to higher accuracy requirements. The Lane property is used by the platoon leader while deciding for any platoon operation.

Similar to the vehicle datatype properties, the platoon datatype properties can be extended.

3.2.3 *Platoon Operation*

Any platoon, degenerated or proper, needs to execute a set of functions to achieve coordinated movement and to adjust with the rest of the traffic. The *state* of a platoon describes platoon's current status or the last completed operation. For example, during the merge operation, the state of the platoons could be 'maneuver ongoing' or after leader selection, the state could be 'agreed on platoon leader'. A finite number of platoon states can be defined based on the implementation and a platoon always be in one of these defined states. The decision of any platoon operation is taken only by the platoon leader, whereas it is executed by platoon members. The relation between platoon states and platoon operations are shown in Figure 10.

The behavior of a platoon can broadly categorized as maintenance of state or information, communication, decision making, and performance of the operation. All of the *Atomic functions* discussed next belongs to any one of this category. A platoon leader maintains or updates platoon state and platoon information. Platoon leader also monitors state and verifies condition in order to take a decision regarding any operation. The platoon leader initiates lead selection, performer selection, and information sharing in order to perform the operation. After completion of an operation platoon leader commits the completion of the operation that initiates change in platoon state and platoon information.

Any platoon action or reaction to a traffic scenario can be defined by a set of functions. *Atomic functions* are the base level of abstraction, implying that further decomposition of an atomic function is not required for specifying the operation of a platoon. The execution of any of the identified atomic functions does not make any change in the platoon structure, but in various combinations they form the operations that a platoon performs. An operation can be *primitive* or *derived* depending on the set of functions involved in the operation. Formally, a platoon operation is defined as:

$$\begin{aligned} \text{Operation} \sqsubseteq\ & \text{isSetOf.AtomicFunction} \\ & \cap \text{performedby.Platoon} \\ & \cap \text{performedby.Vehicle} \end{aligned} \tag{5}$$

3.2.3.1 *Atomic function*

Eight *atomic functions* can be defined that can represent any platoon operation by changing their order of occurrence. These eight atomic functions are as follows:

1. *Verify condition* - This is the first step of any operation in which the platoon leader verifies operation related basic conditions.

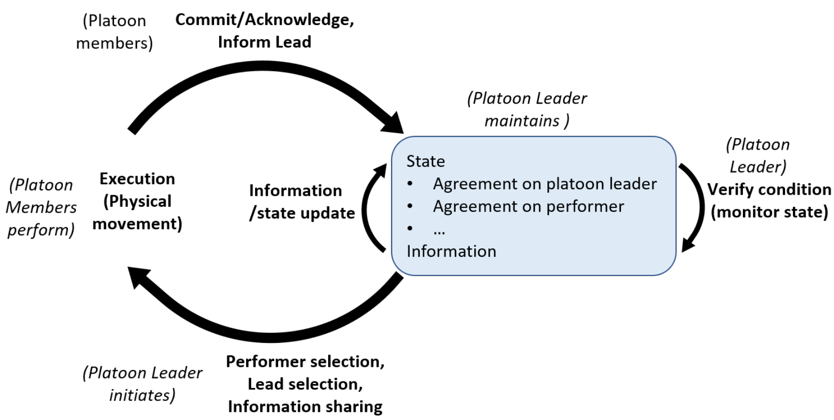


Figure 10: Relation between platoon states and platoon operations.

For example, before initiating a merge operation, a platoon leader checks the platoon's current size and capacity, and checks the route similarity of the two merging platoons.

2. *Lead selection* - This atomic function identifies the platoon leader in the operations like merge and split. In the merge operation the atomic function considers two platoons and decides who will be the upcoming leader after merge. Similarly, for split operation this atomic function decides the leader of the new sub-platoon i.e. the first member after the split point. The leader selection may depend on different criteria such as vehicle sizes, or the route to travel.

3. *Execution* - The execution function covers all the physical movements of platoon members involved with operations such as merge and split, including making a gap, reducing a gap, or a lane change of the platoon or parts of it.

4. *Performer selection* - The performer refers to the platoon or sub-platoon that performs the execution. The lead selection atomic function only selects the leader of the upcoming platoon but does not decide which platoon or sub-platoon will perform the execution. The performer selection atomic function decides the performer. For example, in a merge operation of two platoons the function decides which platoon will perform the merge. Performer selection can be done based on different criteria, such as smaller platoon (sub-platoon) can be chosen as the performer, or performer can be selected depending on the lane clearance.

5. *Information sharing* - The information sharing within the platoons can be of different types based on the shared information and the vehicles initiating the sharing of information.

   Case 1: When a platoon merges with another platoon at the end position, the merging platoon shares its own platoon information with the other platoon leader.

   Case 2: When a platoon merges with another platoon at the front position, the information of the other platoon is passed to the upcoming platoon leader.

   Case 3: When a platoon leader leaves a platoon, it shares its platoon information with the next leader.

6. *Information update* - The platoon information is maintained in two levels. The platoon leader maintains information about the platoon as a whole as well as copies of the vehicle information the other members shared with the leader. In addition, each platoon member maintains its own information. The platoon leader

updates the platoon knowledgebase also with the new information shared by other platoon leaders in merge and split operations. A platoon follower updates any dynamic information locally as directly sensed (e.g., speed) or when it is instructed by platoon leader (e.g., change of leader).

7. *Commitment* - At the end of every successful execution, the performing platoon leader commits to the non-performing platoon leader about the execution completion and success. Without commitment, an execution is treated as incomplete or unsuccessful.

8. *Inform lead* - This atomic function is available to platoon followers to inform their platoon leaders in an unsolicited manner in different scenarios. For example, if a platoon, say, platoon A, wants to merge with another platoon, say, platoon B. Platoon A is closer to the tail portion of platoon B, but outside the communication range of the leader of platoon B. In this case, the merge request generated by platoon A, is sensed by the followers of platoon B and passed to the platoon leader through an inform lead atomic function. This atomic function is also used in exceptional emergency situations, such as a flat tyre.

3.2.3.2 *Primitive operation*

The above mentioned eight atomic functions can define any required operation. An operation is considered as primitive if it is composed of only atomic functions. The primitive operations can be further used to compose derived operations. Application of a primitive or a derived operation results in a change of the platoon structure. Only two primitive operations are identified: *merge* and *split*.

MERGE Merge is a primitive platoon operation where one platoon merges at the end or at the front of another platoon. This operation consecutively executes seven atomic functions as shown in Algorithm 1.

The variables and the parameters are used in the algorithm have following meaning.

- $PlatoonLeader$ upcoming platoon leader after merge operation, selected from two candidate platoons
- $PassiveLeader$ the other platoon leader
- PP is the performing platoon
- NP is the non-performing platoon

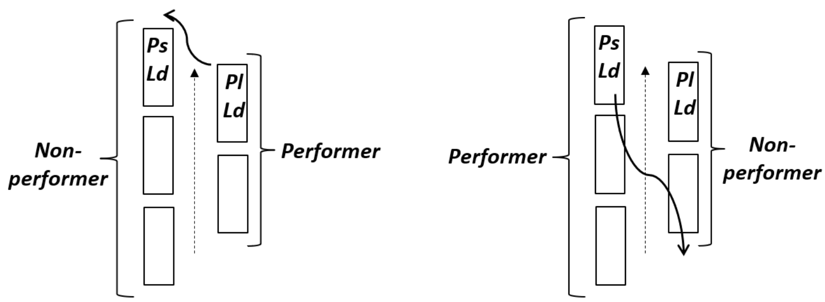
In a merge operation, the participating candidates can be i) two proper platoons ii) one proper platoon and one degenerated platoon

Algorithm 1: Primitive platoon operation: merge

Input: A, B : platoon.
Output: A or B : extended platoon A or B.

```
begin
    if checkMergeCondition(A, B) then
        PlatoonLeader ← selectLead(A, B)
        PassiveLeader ← (A.PlatoonLeader ∪
          B.PlatoonLeader) − PlatoonLeader
        PP ← selectPerformer(A, B)
        NP ← (A ∪ B) − PP
        AorB ← executeMerge {
                if !sameLane then
                    laneChange(PP)
                endif
                reduceGap(PP)
        }
        commit(PP.PlatoonLeader, NP.PlatoonLeader)
        informationShare(PassiveLeader, PlatoonLeader)
        informationUpdate{
                if PlatoonLeader = PP.PlatoonLeader then
                    NP.updateInfo()
                endif
                else
                    PP.updateInfo()
                endif
                PlatoonLeader.addInfo()
        }
    endif
end
```

iii) two degenerated platoons. The merge operation is initiated when one platoon leader sends merge request along with some of platoon information to another platoon. On receiving, the receiver platoon leader verifies the merging conditions (line 2). Conditions may include but are not limited to the platoon size limit, a common path of traveling, or the speed of vehicles. If the two candidates meet the merge conditions, in the next step (line 3) the upcoming platoon leader is determined. The leader of the other platoon is treated as the passive leader. In the following step, the performer candidate is decided using the performer selection atomic function (line 5). The performer candidate executes the merge operation (line 7-12) by changing lane if required, and by reducing the gap between the platoons to obtain the pre-decided inter-platoon gap. This algorithm considered same performer for the lane change and reduce gap function. But, a performer could be different for two different functions. On completion of the merge operation, the performing platoon leader commits the completion to the non-performing platoon leader (line 13). Then the passive leader passes its platoon information to the upcoming platoon leader (line 14). Finally, the follower platoon members update their local databases as per the platoon leader's instruction, and the platoon leader updates its knowledge base for the information of the new platoon members (line 15-23). There are two distinct cases of platoon merge depending on whether the lead platoon will perform the merge operation or the follower platoon will perform the merge operation, as shown in Figure 11.



(a) Performer platoon having platoon leader merges at front

(b) Performer platoon having passive leader merges at tail

Figure 11: Platoon merge operation.

Other than two proper platoons merging, there are three specializations of the merge operation:

1. *Single tail merge* - The single tail merge refers to a merge of a degenerated platoon at the end of a proper platoon. In the single tail merge, the degenerated platoon is not likely the upcoming platoon leader, but generally selected as the performer. After executing the merge, the information of the degenerated platoon

is passed to the upcoming platoon leader and added to the platoon knowledge base.

2. *Single front merge* - The single front merge refers to a merge of a degenerated platoon at the front of a proper platoon. In the single front merge, the degenerated platoon is generally selected as a performer as well as the upcoming platoon leader. After executing the single front merge, the information of the proper platoon is passed to the degenerated platoon, i.e., the new platoon leader. The new platoon leader adds this information to its platoon knowledge base. All the platoon followers update their local knowledge base about the new platoon leader.

3. *Birth* - Birth refers to a merging of two degenerated platoons. It results in the formation of a proper platoon. In this case, the platoon leader and performer are decided as per the lead selection and performer selection criteria.

When a proper platoon and a degenerated platoon merge, the two possible options are a single tail merge and a single front merge. Among these two operations, the single tail merge is preferred from the perspective of information exchange and update. For single tail merge the platoon leader remains unchanged. Hence, the information exchange can be largely reduced: the platoon knowledge base is only updated for the single added vehicle's information, and only the single added vehicle has to update its local knowledge base. Whereas, a single tail merge could be costlier in terms of merge time and fuel expenditure when the degenerated platoon precedes the proper platoon. In this case, the catch up distance for single tail merge is more for the degenerated compared to single front merge.

SPLIT Split is the second primitive operation performed by a platoon. In this operation, a single proper platoon splits into two parts. Each part may produce a proper platoon or a degenerated platoon. In the split operation,the seven basic functions defined above are executed as lined out in Algorithm 2.

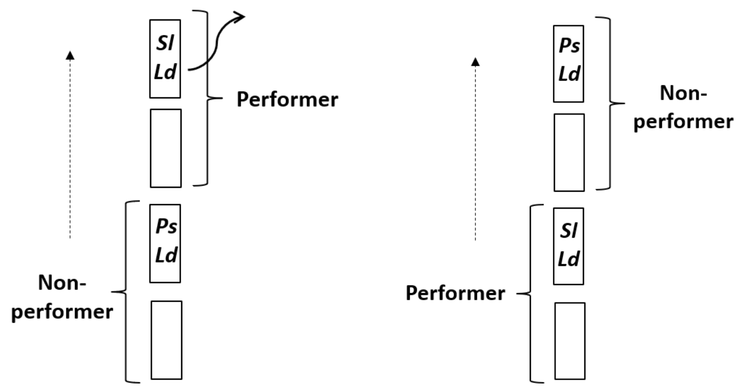
First, the existing platoon leader realizes the requirement of a platoon split and validates the split conditions. A split may be required for various reasons such as an upcoming bridge of limited load bearing capacity, or a part of a platoon having a different destination and thus requiring a split midway. When realizing a split requirement, the existing platoon leader identifies the part of the platoon *executing* the split (line 3-6). The leader of the performing platoon part is called *split leader*. The non-performing part of the platoon has a *non-performing leader*. Next, if the non-performing platoon leader is the same as the existing platoon leader, then the existing platoon leader shares the information of the performing part with the split leader. In the opposite case, the existing platoon leader, leading the split, shares the

Algorithm 2: Primitive platoon operation: split

```
Input: A : platoon.
Output: A, T : sub platoons of A.
begin
    if checkSplitCondition(A) then
        PP ← selectPerformer(A)
        SplitLeader ← selectLead(PP)
        NP ← (A − PP)
        PassiveLeader ← selectLead(NP)
        if A.PlatoonLeader = PassiveLeader then
            informationShare(A.PlatoonLeader, SplitLeader)
        else
            informationShare(A.PlatoonLeader, PassiveLeader)
        endif
        A, T ← executeSplit{
                makeGap(PP)
                if required then
                    laneChange(PP)
                endif
        }
        commit(SplitLeader, PassiveLeader)
        informationUpdate{
                if A.PlatoonLeader = PassiveLeader then
                    PP.updateInfo()
                    PassiveLeader.deleteInfo()
                else
                    NP.updateInfo()
                    SplitLeader.deleteInfo()
                endif
        }
    endif
end
```

information about the non-performing part of the platoon with the non-performing leader (line 7-10). Then the performer executes the split by making a gap to the non-performing part, and by changing the lane if required (line 12-17). On completion of the split, the split leader commits the completion to the non-performing leader (line 18). Finally, the platoon members' information are updated based on which part splits off. The non-performing leader/split leader deletes the non-member information from the platoon knowledge base (line 19-27).

There are two distinct cases of platoon split depending on whether the first part of the platoon will perform the split operation or the last platoon will perform the split operation as shown in Figure 12.



(a) Performer is selected from front (b) Performer is selected from tail

Figure 12: Platoon split operation.

Similar to the merge operation, platoon split also has three specialized cases:

1. *Single tail split* - In this operation, the last platoon follower gets separated from the platoon. Single tail split generates a sub-platoon and a degenerated platoon. As, only the last member separates out, its information is deleted from platoon knowledge base. No other information update is required.

2. *Single front split* - In this operation, the platoon leader gets separated from the platoon. As the platoon leader separates out, all platoon follower information need to be passed to the new platoon leader. Also, platoon followers need to update their local knowledge base about the new platoon leader. Single front split generates a sub-platoon and a degenerated platoon.

3. *Death* - When a platoon consists of only two members a single platoon leader and a single platoon follower, split operation results in two separate degenerated platoons. On completion of split, the platoon leader deletes platoon follower information

from platoon knowledge base and platoon follower updates information about platoon leader. Similar to the merge operation single tail split is cost-effective in terms of information exchange and update.

3.2.3.3 *Derived operations*

An operation is considered as *derived* if it can be represented as the aggregation of one or more primitive operations and atomic functions, or by recursive use of a single primitive operation. An application of a derived operation on a platoon results in a change in the platoon structure. This section describes two derived platoon operations: the *middle merge*, the *change of leader*. Other derived operations such as *group middle merge*, *single middle split*, or *group middle split* can also be composed with the defined primitive operations and atomic functions.

MIDDLE MERGE In the middle merge operation, a platoon (assume the second platoon) enters in the middle of an existing (assume first) platoon. One reason of allowing middle merge could be ensuring togetherness of the vehicles traveling to the same destination. Algorithm 3 presents the derive operation of middle merge.

Algorithm 3: Derived platoon operation: middle merge

Input: A, B : two proper platoons
Output: A : extended platoon A.

```
1 begin
2     if checkManoeuvreCondition(A) then
3         A, T ← split(A)
4         A ← merge(A, B)
5         A ← merge(A, T)
6     endif
7 end
```

In this operation, at first the platoon leader verifies the middle merge conditions (line 2). Then the first platoon splits (line 3) into two parts based on the position the second platoon is allowed to get in. This position is decided by the first platoon leader. Then the second platoon performs a merge operation (specifically, single tail merge or create or merge) with the front part of the first platoon (line 4). After completion of this merge operation, the second part of the first platoon performs a second merge operation (specifically, single tail merge or merge) with the extended front part of the platoon (line 5). The steps of the middle merge operation is shown in Figure 13. Alternative to the proposed sequence, the middle merge can be composed by execute (creating gap), merge, execute (reducing gap), and information update operations. In this alternative, the required gap for merge operation depends on the size of the second platoon. But, this gap is again constrained by the first platoon communication range. Therefore, to generalize the operation, middle merge is defined by the sequence split, merge, merge primitive operations.

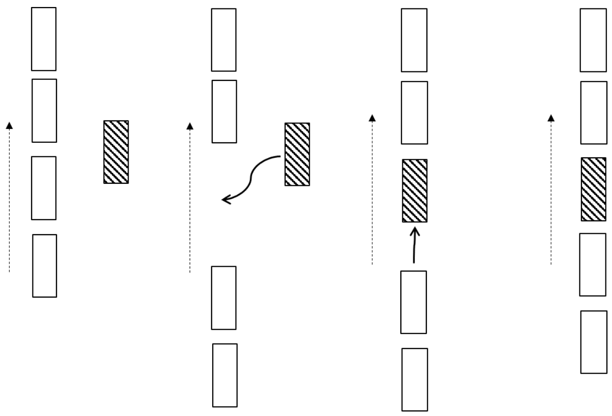


Figure 13: A degenerated platoon member performs middle merge by one split and two merge operations.

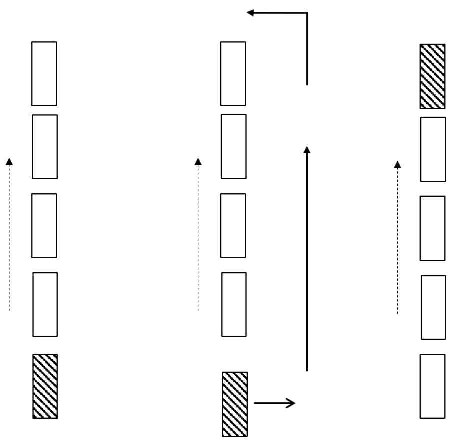
CHANGE LEADER In platooning, due to the air drag the platoon leader has an additional fuel consumption compared to the other members of a platoon. The change leader operation facilitates the alteration of the platoon leadership. Algorithm 4 shows the operations of leader change. In this operation, the platoon leader verifies the

Algorithm 4: Derived platoon operation: change leader

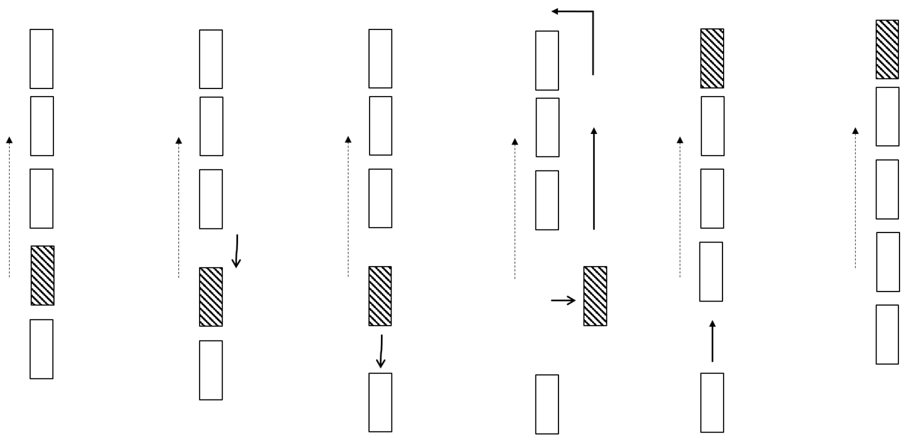
Input: A : proper platoon
Output: A : restructured platoon A.

```
1  begin
2      if checkManoeuvreCondition(A) then
3          A, T ← split(A)
4          if A.LastMember ≠ T then
5              T, R ← split(T)
6              A ← merge(A, R)
7          endif
8          A ← merge(A, T)
9      endif
10 end
```

conditions of changing leader (line 2). Next, the platoon is split into two parts (line 3). The front part (Platoon A) containing the existing platoon leader and the tail part (Platoon T) being led by the upcoming platoon leader. If the tail part is not a degenerated platoon, then a second split (specifically, single front split) takes place that results in another two platoons, a degenerated Platoon T i.e. the upcoming platoon leader, and a platoon R (line 5). The platoon T changes the lane in order to allow R to merge back to platoon A (line 6). Finally, platoon T merges with the platoon A by a single front merge (line 8). The two cases of change leader operations are shown in Figure 14. In the first case the last member of the platoon becomes the new platoon leader and in the second case a middle member of the platoon becomes the new platoon leader.



(a) Tail platoon member performs change leader by split and merge operation



(b) Middle platoon member performs change leader by two split and two merge operations

Figure 14: Platoon change leader operation.

In case any function or operation fails to execute, the involved platoons revert back to their initial states (roll-back).

3.3 ILLUSTRATION OF THE IMPLEMENTATION

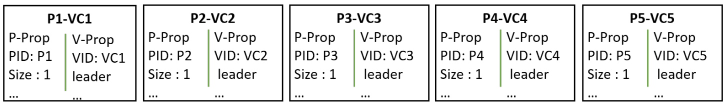
All the platooning concepts, platoon atomic functions and primitive operations have been implemented in MATLAB environment. Derived operations have been generated with the help of these building blocks, according to Algorithms 3-4. In order to illustrate the flow of functions and communications within a derived operation, in the following the consecutive steps of a *middle merge* is shown for a given scenario (Figure 15).

In this scenario, five degenerated platoons are instantiated (Platoon P1 to Platoon P5). The first four of them are merged together to form a proper platoon under the leadership of Platoon 1, i.e., the aggregate platoon has (still) the platoonID P1. Then Platoon P5 performs a middle merge with the proper platoon Platoon P1. For this purpose, the platoon leader of Platoon P1 decides to:

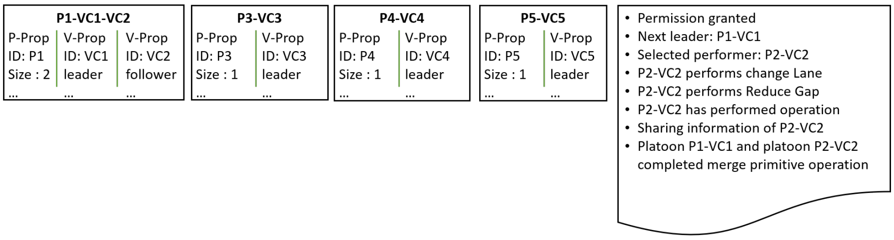
1. split between the second and third platoon member;
2. assign the third member to become the *split leader*, and also, with its followers, to become the *performing* platoon;
3. assign to itself, together with its own follower, the role of the non-performing platoon.

The split operation results in two (proper) platoons, namely Platoon P1 (front, non-performing) and Platoon P2 (tail, performing).

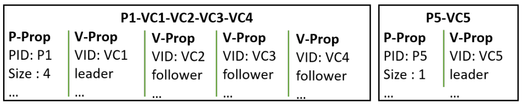
Next, Platoon P5 merges with Platoon P1, resulting in an extended Platoon P1 of three members. Finally, Platoon P2 merges with Platoon P1 to complete the middle merge operation, resulting in an extended Platoon P1 of five members.



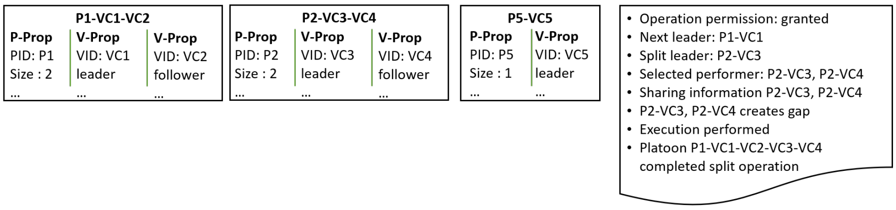
(a) Phase I : Platoon initiation



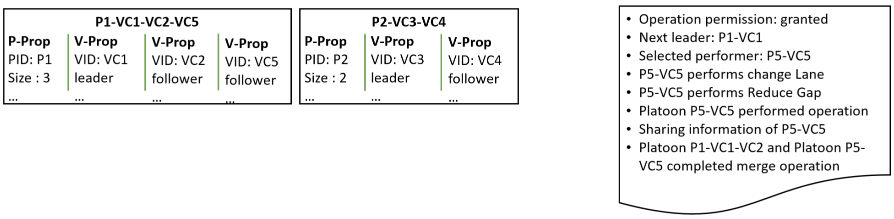
(b) Phase II : Merge primitive operation - birth of platoon



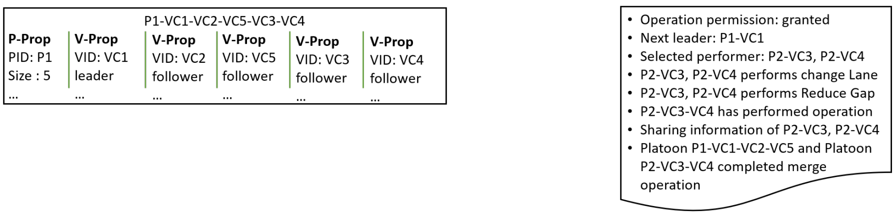
(c) Phase III : Proper platoon of four members and one degenerated platoon



(d) Phase IV : Platoon split, first operation for middle merge



(e) Phase V : Merge operation, second operation for middle merge



(f) Phase VI : Merge operation, third operation for middle merge

Figure 15: Platoon behavior - illustration.

3.4 DISCUSSION

The previous section develops a small set of atomic functions. These atomic functions are combined to produce two primitive operations, *merge*, and *split*. The claim, or the hypothesis, of this research is that any behavior of platoons presented in the existing research literature can be represented as a derived operation. Since a proof of this claim is impossible by deduction, the research starts an inductive proof. Two derived operations, namely, *middle merge* and *change leader* are illustrated to show how the primitive operations can be aggregated to define these two platoon operations. Other than these two operations other forms of complex behavior that is the derived operations are also analyzed to support this claim. The claim can be upheld as long as no other complex behavior can be found that cannot be represented by combining these atomic functions and primitive operations.

A related claim is that the set of atomic functions is minimal: none of them can be given up (they are all used at some stage in the primitive and derived operations), and none of them can be replaced by one of the other functions, or a combination thereof.

A further effort toward the proof by induction can be made by going back to the different platooning projects discussed in the literature review above. Their classes, properties, and operations must be able to be represented by the elements of the ontology presented in this research. Accordingly, Table 1 shows the mapping of the various platooning *objects* to the proposed concepts.

Most of the reviewed projects use at least three types of objects: *platoon leader*, *platoon follower*, and *platoon*, and sometimes additionally the concept of a free *vehicle* in various relations to a platoon. The only exception is SARTRE (Bergenhem et al., 2010; Robinson, Chan, and Coelingh, 2010), which lists eight platoon objects. In contrast, the proposed conceptualization uses only a platoon class and a vehicle class, where every vehicle is either platoon leader (potentially with no followers) or platoon follower. Note, vehicles without platooning capability are not considered in the proposed conceptualization as they cannot be part of a platoon. The table illustrates that these two classes are sufficient.

The literature also addresses some platooning operations. Table 2 shows how those operations can be described with the proposed set of atomic functions and primitive operations.

The project SARTRE differentiates between *create* and *join* operations on one hand, and *leave* and *dissolve* operations on the other, as they have defined platooning objects. Most of the other projects assume that a platoon is created at the starting point and destroyed at the endpoint, and focus on behavior in between, where one or more vehicles can merge or leave the platoon. Thus they do not consider *create* or *destroy* of a platoon on the fly (Deng, 2016). Amoozadeh et al. (2015) define three basic platoon maneuvers: *merge*, *split* and *lane change*, and then illustrate three platooning scenarios: the leave of leader, the leave of a follower and the entry of a vehicle at the end of the platoon. This research avoided the lower level operational details that include control operations, such as how to maintain a constant

Literature/ Project	Object class mapping: Literature object	Interpretation	Proposed object
SARTRE	FV (Following Vehicle)	a vehicle, truck, bus or car, in a platoon behind an LV	platoon follower
	LV (Lead Vehicle)	LV is the lead vehicle of a platoon and is a truck or bus	platoon leader
	OV (Other Vehicle)	a vehicle that will never join a platoon but may affect it	not considered
	PFV (Potential Following Vehicle)	a PFV is not currently platooning, but may do so. When in a platoon this vehicle is an FV	platoon leader
	PLV (Potential Lead Vehicle)	a PLV is not currently leading a platoon, but may do so. A PLV in a platoon becomes LV	platoon follower
	PPV (Potential Platoon Vehicle)	a vehicle that may be included in a platoon. PPV is controlled manually. A PPV in a platoon is either an FV or LV	platoon leader
	PV (Platoon Vehicle)	an LV or FV. In the case of FV it is controlled autonomously	vehicle
	Platoon	a platoon is a number of vehicles travelling together and electronically connected (e.g. via wireless communication). There is one LV and one or more FVs	platoon
PATH	lead car/vehicle	vehicle leads the platoon	platoon leader
	preceding car/vehicle	vehicle follows the platoon	platoon follower
iQFleet	lead vehicle/platoon leader	vehicle leads the platoon	platoon leader
	follower/ platoon follower	vehicle follows the platoon	platoon follower
Platoon management	platoon leader	vehicle leads the platoon	platoon leader
	follower	vehicle follows the platoon	platoon follower

Table 1: Mapping of platooning object concepts.

Literature/ Project	Operation mapping		
	Literature operation	**Interpretation**	**Proposed operation**
SARTRE	create	a PLV and a PFV initiates a new platoon	merge (create)
	join	a PLV or PFV joins a platoon	merge
	maintain speed	longitudinal or lateral position of one or more FVs are adjusted	execute
	leave	LV or FV leaves the platoon	split
	dissolve	LV or FV leaves the platoon of two members	split (destroy)
PATH	lane keeping	platoon members maintain the same lane	execute
	lane change	vertical movement of platoon member	execute
	entry/join	vehicle enters to a platoon	merge
	exit/split	vehicle leaves from a platoon	split
iQFleet	platoon acceleration/deceleration	the platoon accelerate/decelerate	execute
	inter-vehicle distance adjustment	makes larger gap (e.g. near ramp to enhance safety), or reduce gap (to save fuel)	execute
	speed planning	deciding optimum speed to save fuel	not considered as operation
	platoon formation	creation of platoon	merge
	platoon disaggregation	leaving of a platoon member	split
Platoon management	merge	merging of two platoons	merge
	split	splitting of a platoon in two sub-platoons	split
	lane change	change of lane	execute
	leader leave	leader leaves the platoon	split
	follower leave	any of the followers leaves platoon	split/single middle leave
	entry	a free vehicle joins at end	merge

Table 2: Mapping of platooning operation concepts.

intra-platoon gap, how to maintain a particular speed, or how to accelerate or decelerate. This is done for a good intention – to keep an open space for developers as per the implementation requirement. This research assumes these operations are implicit in the defined eight atomic functions.

3.5 SUMMARY

In this chapter, platooning objects, platoon properties, and platooning operations are conceptualized and formally specified in an OWL ontology. The platooning objects are abstracted and defined by their platooning characteristics. Some platoon properties are identified that play a significant role in a platoon's decision-making process. However, these properties can be extended in order to apply additional rules in platooning operations. In contrast, the identified operations are abstracted in three different layers. The bottom layer represents the basic blocks of platoon operations, termed *atomic functions* since they do not need to be further decomposed in order to represent conceptual platoon behavior. In the middle layer, *primitive operations* are defined that are composed only of the atomic functions. The top layer of abstraction defines the *derived operations* that can be composed of atomic functions and primitive operations. It has been shown that the defined platooning atomic functions and primitive operations are capable of representing all platoon behaviors reported in the literature, and until proven otherwise claim to be capable to represent any platoon behavior. Platoon atomic functions and primitive operations are assumed to be minimal, and derived operations are arbitrarily extendable. As the ontology is designed with help of OWL DL, a reasoning module can be added as the extended version of this work to support advance decision-making system in a platooning environment. The research proposed a way of standardization of concepts for ad-hoc platooning. The platooning communities yet to accept this standardization and enhance this conceptualization as per their requirement.

4 MODELING

The previous chapter conceptualized the platoon objects, properties and platoon operations in order to standardize them. The next three chapters: Chapter 5 to Chapter 7 present implementation and analysis of the platoon operations in the simulation environment based on the proposed conceptual model.

Vehicle platooning is a complex system with a number of interacting models. This chapter describes the basic models, suitable for vehicle platooning and commonly used in the next three chapters to simulate platoons. The details of the car-following model, lane change model, fuel consumption model, and network model are explained in particular. This explanation is useful to understand the requirement and functionality of each of the models.

Any traffic flow can be modeled in at least three different ways, namely, 1) macroscopic model, 2) microscopic model, and 3) mesoscopic model (Barceló et al., 2010). In macroscopic approach of modeling, 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 this research aims to observe and model the microscopic parameters such as the speed, acceleration, relative position of the vehicles to the platoon. Hence, SUMO, microscopic open-source traffic simulator is used to model the simulations and to perform the experiments under consideration.

The chapter is organized as follows. Section 4.1 describes the longitudinal dynamics and Section 4.2 describes the lateral dynamics of the vehicles and the platoon. Section 4.3 explains the fuel consumption model used to compute fuel consumption. Section 4.4 presents the components and the creation of the road network used in the simulation. Section 4.5 provides a summary of the chapter.

4.1 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. 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. One for the free-flow vehicles and another for the platoons.

The free flow vehicles can adopt any standard car-following model available in the simulation platform. This research adopts the Intelligent Driver Model (IDM) (Treiber, Hennecke, and Helbing, 2000) for free flow vehicles. The reason for selecting IDM is, it has detailed documentation and this model is widely used in the literature (Bieker-Walz et al., 2017; Liu, Zhu, and Yang, 2016). According to this model, the acceleration a_t of a vehicle is determined by Eq. 6 and Eq. 7:

$$a_t = a \left[1 - \left(\frac{v_\alpha}{v_0} \right)^\delta - \left(\frac{s^* \left(v_\alpha, \Delta v_\alpha \right)}{s_\alpha} \right)^2 \right] \tag{6}$$

where s^* is computed by:

$$s^* \left(v_\alpha, \Delta v_\alpha \right) = s_0 + t v_\alpha + \frac{v_\alpha \Delta v_\alpha}{2\sqrt{ab}} \tag{7}$$

The parameters have the following meanings:

- v_0 is the velocity the vehicle would drive on a free road
- v_α is the velocity of the vehicle
- $v_{\alpha-1}$ is the velocity of the previous vehicle
- $\Delta v_\alpha = v_\alpha - v_{\alpha-1}$
- s_0 is the minimal distance to the vehicle in front; also in complete standstill
- x_α is the position of the vehicle
- $x_{\alpha-1}$ is the position of the previous vehicle
- $l_{\alpha-1}$ is the length of the previous vehicle
- $s_\alpha = x_{\alpha-1} - x_\alpha - l_{\alpha-1}$
- t is the desired safety time headway to the vehicle in front
- a is the acceleration
- b is the comfortable braking deceleration
- δ is the acceleration exponent

The platoons adopt the suitable CACC car-following model of SUMO (Milanés and Shladover, 2014; Xiao, Wang, and Arem, 2017; Xiao et al., 2018) for the longitudinal movement with three modes of control, namely speed control mode or cruising mode, gap control mode and, the gap-closing control mode.

SPEED CONTROL MODE OR CRUISING MODE The speed control mode is designed to maintain the desired speed and is applicable when there are no preceding vehicles in the range covered by the sensors or when the time-gap is larger than 2 s. In this mode the vehicle's acceleration is modeled by Eq. 8.

$$a_t = k_0(v_0 - v_{err}) \tag{8}$$

In this equation, the control gain k_0 is a parameter for determining the rate of speed error v_{err} for acceleration and v_0 is the desired cruising speed.

GAP CONTROL MODE The gap control mode aims to maintain a constant time gap between platoon members. In this mode, a vehicle's speed is calculated by the speed of the vehicle in the previous time step, the gap error in the previous time, and its derivative as per Eq. 9.

$$v_t = v_{t-1} + k_p(e_{t-1}) + k_d \dot{e}_{t-1} \tag{9}$$

where the gap error e_t is computed by:

$$e_t = x_{\alpha-1} - x_\alpha - l_\alpha + t(v_{\alpha-1}) - d_0 \tag{10}$$

Here, the dynamic spacing margin d_0 was formulated as a function of vehicle speed, which gives additional clearance at low speeds to prevent rear-end collisions. For CACC, the d_0 is determined as,

$$d_0 = \begin{cases} 0 & \text{for } v_t \geqslant 10 m/s \\ -0.125 v_t + 6.25 & \text{for } v_t < 10 m/s \end{cases} \tag{11}$$

In Eq. 9, Eq. 10 and Eq. 11 the parameters have the following meanings:

- v_t is the velocity of the vehicle at time t
- v_{t-1} is the velocity of the vehicle at time $t-1$
- k_p and k_d are the feedback gains
- e_t is the gap error at time t
- e_{t-1} is the gap error at time $t-1$
- $\dot{e}_{t-1}$ is the derivative of e_{t-1}

- x_α is the position of the vehicle
- $x_{\alpha-1}$ is the position of the previous vehicle
- l_α is the length of the vehicle
- t is the desired safety time headway to the vehicle in front
- $v_{\alpha-1}$ is the velocity of the previous vehicle
- d_0 is the dynamic spacing margin

GAP-CLOSING CONTROL MODE The gap-closing controller enables the smooth transition from speed control mode to gap control mode. This control mode is triggered when the time-gap is less than 1.5 s. If the time-gap is between 1.5 s and 2 s, the CACC-equipped vehicle retains the previous control strategy to provide hysteresis in the control loop and perform a smooth transfer between the two strategies.

This research used the CACC car-following model to ensure string-stability during platoon's longitudinal movement. However, the communication aspects of CACC are not implemented as the research goal is mainly to analyze different aspects of platoon operations. Hence, communication effects such as communication delay or disturbances are irrelevant and neglected here. Despite simplifications, these two car-following models are suited to analyze all the scenarios under consideration.

The simulation uses the standard values of the parameters referred to the literature (Johansson et al., 2016; Liang, 2016) and SUMO standard setting[1] as listed in Table 3.

4.2 LANE CHANGE MODEL

Along with the longitudinal control, lane change model is needed for the vehicle's lateral control on multi-lane roads. The lane-changing model handles two factors. It computes the lane change decision of a vehicle in each simulation step based on the route of the vehicle and the current and historical traffic conditions of the surrounding vehicles. It also computes the speed of the vehicle under consideration and the surrounding vehicles to perform the desired lane change (Erdmann, 2014).

There are different types of lane change. 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. When a vehicle reaches to a dead end, the vehicle is compelled to change its lane.

1 Vehicle Type Parameter Defaults - SUMO Documentation, https://sumo.dlr.de/docs/Vehicle_Type_Parameter_Defaults.html, accessed August 14, 2019

Parameter	Value
Minimum gap at stand-still s_0	2 m
Safe time headway t	2 s
Acceleration a	1 m/s²
Deceleration b	4 m/s²
Maximum deceleration b	7 m/s²
Acceleration component δ	4.0
Vehicle length l	18.0 m
Intra-platoon headway h	10 m
Maximum speed allowed in road v_{max}	28 m/s
Minimum speed preferred in road v_{min}	16 m/s
Control gain k_0	0.4 s^{-1}
Feedback gain k_p	0.45 s^{-2}
Feedback gain k_d	0.25 s^{-1}

Table 3: Common parameters used in the simulation.

This type of lane change is termed as *strategic lane change*. A strategic lane change is performed based on four components: evaluating the subsequent lanes, determining the urgency of lane change, speed adjustment of the vehicle and preventing a deadlock situation. Evaluation of the subsequent lanes helps to determine the sequence of lanes - *bestLanes* that can be followed without lane changing up to the next dead-end or to a maximum distance and lane corresponding traffic density. The urgency of lane change is decided on different factors such as remaining distance to the dead-end, look ahead speed, traffic density of the intermediate and target lanes. Whenever the desired lane change cannot be executed due to blocking vehicles, a vehicle may adjust its speed to perform the lane change in later steps. Prevention measures are taken to avoid a deadlock situation where a vehicle needs to stop on a dead lane, as a lane change is not possible. Other than the strategic lane change, there is also a *cooperative lane change* where a vehicle performs lane change to help another vehicle with lane change. In a *tactical lane change*, a vehicle attempts to avoid following a slow leader. It requires balancing the expected speed gains from lane changing against the effort of lane-changing.

A platoon follows the same principle 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 LC2013 lane change model of SUMO. This model is selected as it is the default model of SUMO as suitable 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.

4.3 FUEL CONSUMPTION MODEL

In this research, the fuel consumption of the vehicles is the decisive factor that decides the acceptability of ad-hoc platoon formation and dissolution compared to non-platooning. Therefore, a model is required to compute the fuel consumption of vehicles during the simulation. Several vehicle fuel consumption and emission estimation models are proposed in the literature (Ahn et al., 2002; Bowyer, Akcelik, and Biggs, 1985; Cappiello et al., 2002; Tong, Hung, and Cheung, 2000). Most of them use average vehicle speed and a regression model for the estimation. However, this research requires to count on fuel consumption in every instance. Hence, this research uses an instantaneous fuel consumption model (Johansson et al., 2016; Oguchi and Katakura, 2000) based on thermal efficiency, mechanical efficiency on friction resistance as well as vehicle kinetics. Specially, this model considers the aerodynamic drag component based on inter-vehicle distance and its effect in fuel consumption which is important while computing platoon's fuel consumption. In this model, the instantaneous fuel consumption per unit time is calculated by Eq. 12 and Eq. 13 as below:

$$f_t = \begin{cases} f_{idle} + \frac{v_t}{\eta \epsilon H} F_t & \text{for } F_t > 0 \\ f_{idle} & \text{otherwise} \end{cases} \tag{12}$$

$$F_t = a_t(M + m_e + m_w) + F_a + F_r + F_g \tag{13}$$

The parameters have the following meanings:

- f_{idle} is the idle fuel consumption rate
- v_t is the velocity of the vehicle at time t
- η is the power transmission efficiency
- ϵ is the thermal efficiency of engine
- H is the Heat equivalence of diesel
- F_t is the tractive force produced by the engine
- a_t is the acceleration at time t
- M is the vehicle mass

- m_e is the engine inertial mass
- m_w is the wheel inertial mass
- F_t is the tractive force produced by the engine
- F_a is the aerodynamic drag
- F_r is the rolling resistance force
- F_g is the gravitational force

The parameter values are listed in Table 4.

During the vehicle's movement the forces acting on the vehicle are the tractive force produced by the engine, the braking force, the aerodynamic force function, the rolling resistance force and the gravitational force. The tractive force moves the vehicle forward, while the brake force slows down or stops the vehicle. This research assumes these two forces cannot be applied at the same time. Air drag and roll friction act as resistive forces, while depending on the road grade the gravity can either yield to a resistive or assisting force.

The aerodynamic drag is a resistive force on the vehicle due to the surrounding air. On-road trials have already shown that the air drag resistance can be reduced by aligning vehicles close behind each other in a platoon. The follower vehicle mainly experiences a significant reduction in air drag resistance due to the lowered pressure at its front. The lead vehicle might also experience a reduced air drag if the follower vehicle drives close enough to dissolve the turbulent wake that occurs behind a vehicle. However, the reduction is not as significant as for the follower vehicle. The air drag reduction decays as the inter-vehicle distance increases. The air drag force F_a (Alam, 2014; Liang, 2016) is modeled based on vehicle's speed and inter-vehicle distance as per Eq. 14:

$$F_a = \frac{1}{2} C_D A_a \rho_a v_t^2 \phi(d_r) \tag{14}$$

The parameters have the following meanings:

- C_D is the air drag coefficient
- A_a is the maximum cross-sectional area of the vehicle
- ρ_a is the air density
- v_t is the velocity of the vehicle at time t
- $\phi(d_r)$ is the nonlinear air drag ratio

The value of the air drag ratio is referred to (Humphreys et al., 2016; Liang, 2016). This research assumes for all the platoon followers; the air drag ratio is the same for a specific inter-vehicle distance (intra-platoon headway). Whereas, in reality, the air drag ratio of third platoon member is less than the air drag ratio of second platoon member

(Bruneau, Khadra, and Mortazavi, 2017; Liang, 2016). This assumption increases the fuel consumption of a platoon in some percentage for a platoon of length three or more, but not exaggerate about platoon's fuel benefit. The exact values of air drag ratio will produce a more accurate result.

The gravitational force can influence fuel consumption based on the road grade. This research considers no grade. Therefore the gravitational force does not impact on platoon's fuel consumption. The roll resistance force occurs due to the frictional force between the road and the wheels. The roll resistance force is modeled as Eq. 15:

$$F_r = C_r M g cos\theta \tag{15}$$

The parameters have the following meanings:

- C_r is the rolling resistance coefficient
- M is the vehicle mass
- g is the acceleration due to gravity
- θ is the road grade

The fuel consumption of a platoon is calculated by aggregating the fuel consumption rate of all platoon members over the simulation period. The static parameters of the fuel consumption model and the values used in this research are listed in Table 4. These are the standard settings that are typically used in the literature (Johansson et al., 2016).

4.4 NETWORK MODEL

In the following chapters, different road networks are designed based on the requirements of the simulations. This section provides an overview of the network components and the process of developing road network for simulation.

In this research, all experiments are carried out in the traffic simulator SUMO. An external application MATLAB (Guide, 1998) is used to control the vehicles via the interface TRACI. Vehicles' microscopic behavior such as speed, lane-change are controlled by MATLAB during the platoon maneuver. This research also uses NETEDIT to develop highway networks. The output of the NETEDIT is saved in XML format that contains detailed description of the network. Specifically, it contains the information of edges, junctions and the connection between the the edges. The other details such as length of each edge, priority, speed limit are also mentioned in the XML file. Figure 16 shows a snapshot of two partial networks used in this research and sample XML file of a road network description. (Krajzewicz et al., 2012, 2002).

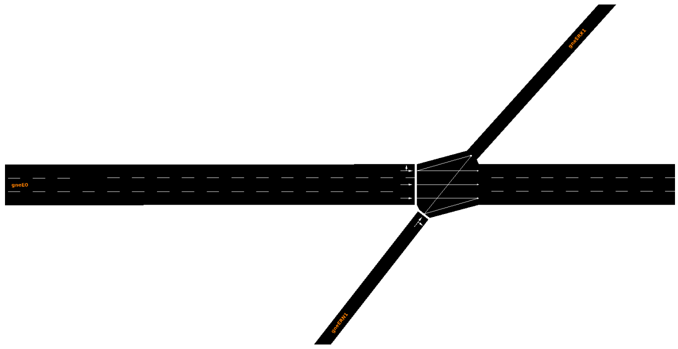
Parameter	Value
Idle fuel consumption rate f_{idle}	0.59×10^{-3} kg/s
Power transmission efficiency η	0.94
Thermal efficiency of engine ϵ	0.44
Heat equivalence of diesel H	44.8×10^{6} J/kg
Vehicle mass M	40,000 kg
Engine inertial mass m_e	0 kg
Wheel inertial mass m_w	0 kg
Air drag coefficient C_D	0.56
Frontal area A_a	10.26 m^2
Air density ρ_a	1.29 kg/m^3
Air drag ratio $\phi(d_r)$	0.9/0.6 first/other platoon members
Rolling resistance coefficient C_r	1.5×10^{-3}
Standard acceleration due to gravity g	9.81 m/s^2
Road grade θ	0

Table 4: Parameters used in the fuel consumption model.

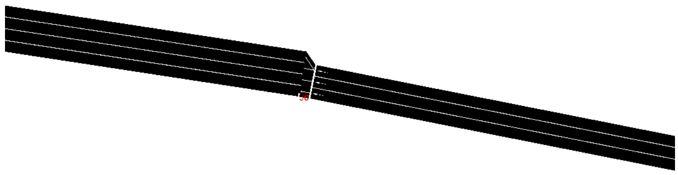
Another XML file is used to define vehicles specification such as vehicle type, length, maximum speed and other parameters. The routes of the vehicles, defined by source, destination and a path are decided randomly and initialized at run time. The configuration file specifies the input and output XML files used in the simulation.

4.5 SUMMARY

This chapter presents the model of the longitudinal and lateral vehicle dynamics used in this research. This serves as the basics for the vehicles' movement and platoon formation and dissolution in the coming chapters. This chapter also describes a fuel consumption model that plays an important role to analyze and compare platoon formation and dissolution strategies. Furthermore, this chapter explains the construction and representation of the simulation network that is commonly used in the following chapters.



(a) A portion of the straight simulation network



(b) A portion of the 3-4 lane simulation network


```xml
<net version="0.27" xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xsi:noNamespaceSchemaLocation=
"http://sumo.dlr.de/xsd/net_file.xsd">

    <location netOffset="0.00,0.00" convBoundary="-59.86,-56.25,4822.24,168.84" origBoundary=
    "-10000000000.00,-10000000000.00,10000000000.00,10000000000.00" projParameter="!"/>

    <edge id="gneE0" from="gneJ0" to="gneJ1" priority="1" length="2000.00">
        <lane id="gneE0_0" index="0" speed="28.00" length="2000.00" shape="-59.85,47.39 131.90,47.53"/>
        <lane id="gneE0_1" index="1" speed="28.00" length="2000.00" shape="-59.86,50.69 131.90,50.83"/>
        <lane id="gneE0_2" index="2" speed="28.00" length="2000.00" shape="-59.86,53.99 131.89,54.13"/>
    </edge>

    <edge id="gneERN1" from="gneJRN1" to="gneJ1" priority="1" length="100.00">
        <lane id="gneERN1_0" index="0" speed="28.00" length="100.00" shape="92.65,-8.80 133.74,43.77"/>
    </edge>

    <edge id="gneERX1" from="gneJ1" to="gneJRX1" priority="1" length="100.00">
        <lane id="gneERX1_0" index="0" speed="28.00" length="100.00" shape="145.18,57.92 195.95,114.36"/>
    </edge>

    <junction id="gneJ0" type="dead_end" x="-59.86" y="55.64" incLanes="" intLanes="" shape="-59.86,55.59 -59.85,45.79"/>
    <junction id="gneJ1" type="unregulated" x="141.04" y="55.79" incLanes="gneERN1_0 gneE0_0 gneE0_1 gneE0_2" intLanes="" shape=
    "143.99,58.99 146.37,56.85 146.87,55.74 146.87,45.94 135.00,42.78 132.48,44.75 131.90,45.93 131.89,55.73"/>

    <connection from="gneE0" to="gneE1" fromLane="0" toLane="0" dir="s" state="M"/>
    <connection from="gneE0" to="gneE1" fromLane="1" toLane="1" dir="s" state="M"/>
    <connection from="gneE0" to="gneE1" fromLane="2" toLane="2" dir="s" state="M"/>
    <connection from="gneE0" to="gneERX1" fromLane="2" toLane="0" dir="l" state="M"/>

</net>
```


(c) Partial XML file describing the road network

Figure 16: Construction of simulation network.

5 THE IMPACT OF FLEXIBLE PLATOON FORMATION OPERATIONS

The core of this chapter has been accepted as Maiti, S., Winter, S., Kulik, L. and Sarkar, S (2019). The Impact of Flexible Platoon Formation Operations. In: *IEEE Transactions on Intelligent Vehicles*. Sant Maiti did this research under the supervision of the co-authors.

The previous chapters already covered the first part of the research, i.e. a conceptualization of the platoon objects, properties and platoon operations and introduced the models and environment used for the platoon simulation. The rest of the chapters focuses on the implementation and the analysis of the platoon operations, platoon formation and dissolution strategies in the simulation environment.

The literature survey has shown that there is comparatively little work on how to form the platoons compared to other areas of platooning, such as platoon control strategies and intra-platoon communication. The literature assumes platoon formation by tail merge, which is sufficient only for formation on a ramp or at a ramp-highway junction. This chapter deals with three different merge operations, namely front merge, middle merge, 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 is quick platoon formation on an average in a higher traffic density in particular. This insight should allow a more flexible toolkit for planning a platoon formation.

5.1 INTRODUCTION

Platooning projects and on-road platooning trials (Bergenhem et al., 2012; Carbaugh, Godbole, and Sengupta, 1998; Lauer, 2011; Lidström et al., 2011; Michael et al., 1998; Rajamani et al., 2000; Robinson, Chan, and Coelingh, 2010; Tsugawa, Kato, and Aoki, 2011) 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 performed on a ramp or at a ramp-highway junction. This research, however, considers 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. The research studies 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* (Dao, Huissoon, and Clark, 2013; Hall and Chin, 2005; Hobert, 2012). The objective was 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.

This chapter 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 (Maiti, Winter, and Kulik, 2017), 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. 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 research aims to address the following research challenges:

1. *Behavior of front merge, middle merge and tail merge operations* - The research implements all three merge operations in a simulation environment considering a single vehicle and a single platoon in the 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.

Hypothesis: 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 operation in a given situation.

In this chapter, provides Section 5.2 describes the basic blocks of the proposed simulation, and Section 5.3 demonstrates the experiments. An analysis of the experimental results and the key insights are presented in Section 5.4. Section 5.5 summarises the chapter.

5.2 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. The research considers that within the communication range of platoon, more than one vehicle may express the merge request. Hence, suitable merging vehicles are selected from the available options. While selecting the merging vehicle, only platoonable vehicles are considered. Point to note, this research considers only a percentage of the traffic is platoonable or willing to platoon. The selected vehicles merge with a platoon one after another until the platoon reaches its maximum size. Therefore, 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 5. The variables and the parameters used in the algorithm have the 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).

Algorithm 5: 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
begin
    P ← InitializePlatoon(N, R, p_is, p_0)
    T ← InitializeTraffic(N, R, v_0)
    isManeuverState(P) = false
    lenP = p_is
    nVeh = null
    while lenP < p_ms do
        if !isManeuverState(P) then
            if isEmpty(nVeh) then
                nVeh ← FindMergingVehicle(P, T, b_len)
                isManeuverState(P) = true
            endif
        endif
        else
            if isOperationTimeOut(P, nVeh, t_out) OR
            isOutofRange(P, nVeh, o_dis) then
                isManeuverState(P) = false
                nVeh = null
            endif
            if isMerged(P, nVeh) then
                SetDesiredSpeed(P, p_0)
                isManeuverState(P) = false
                nVeh = null
                lenP = size(P)
            endif
            else
                spdP ← SetNextIterationSpd(P)
                spdV ← SetNextIterationSpd(nVeh)
                P ← Merge(P, nVeh, spdP, spdV, h)
            endif
        endif
    end
    RS ← Results(merge time, merge distance, merge success rate,
      average traffic speed)
end
```

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).
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, the selection of an improper candidate may lead to failure of the merge operation. As different merging strategies are evaluated 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 17 represents a traffic scenario of front merge where a suitable merging vehicle needs to be selected. In this figure, the platoon P

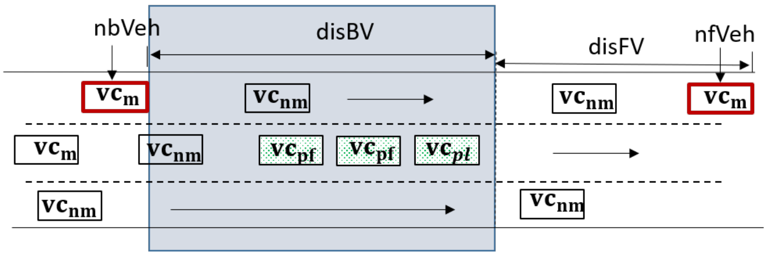


Figure 17: Merging candidate selection.

consists of three vehicles, one platoon leader vc_{pl} and two platoon followers vc_{pf}. The traffic consists of platoonable free flow vehicles vc_m and non-platoonable free flow vehicles vc_{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.

5.2.1 *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, this research proposes a heuristic that identifies the most suitable merging vehicle from the traffic. The details of the selection process are shown in Figure 18. 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*

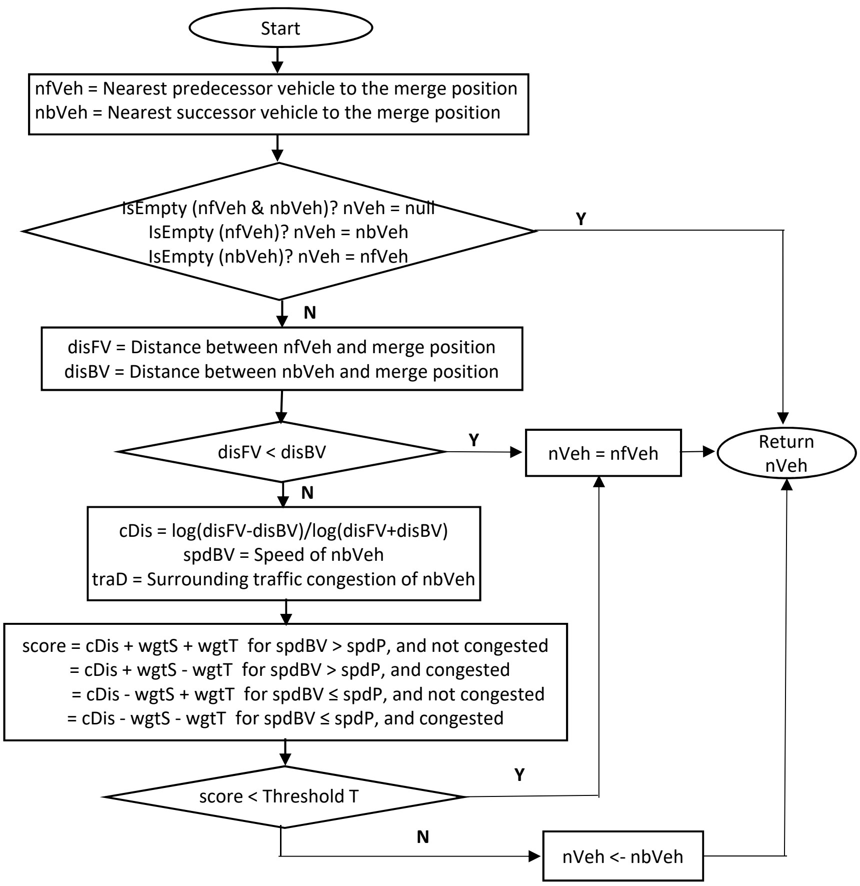


Figure 18: Merging vehicle selection - front and tail merge.

Step 1: Each platoon is associated with a buffer area containing some platoonable vehicles vc_m and some non-platoonable vehicles vc_{nm}. The platoonable vehicles within the buffer area considered as candidates for platoon merge operation. In Figure 17, 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 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*, the distance *disFV* and *disBV* of these two vehicles from the merge position is compared. It is observed 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. 16.

$$\mathrm{cDis} = \frac{\log(\mathrm{disFV} - \mathrm{disBV})}{\log(\mathrm{disFV} + \mathrm{disBV})} \tag{16}$$

The value of *cDis* indicates if *nbVeh* is preferable for merge based on the distance. Instead of using raw distance values $\log$ is used to scale down the comparative distance score between 0 to 1. Few scenarios have been considered 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 the platoon (e.g. 250 m, 50 m, *cDis* is 0.93), and 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, this research assumes 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 17 vehicle vc_{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. To decide the value of *wgtS* several merge testcases are executed and it is set to 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 17 shaded region 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, this research aims not to have more than two vehicles in

the same lane and more than five vehicles in all lanes[1]. If this can not be achieved, a penalty is applied by subtracting a weight *wgtT* from the heuristic. After running several testcases, *wgtT* is set to 0.2.
Step 9: Finally, the heuristic score is computed using Eq. 17.

$$\begin{aligned} \text{score} &= \text{cDis} + \text{wgtS} + \text{wgtT}, && \text{for spdBV} > \text{spdP} \\ & && \text{and no congestion} \\ &= \text{cDis} + \text{wgtS} - \text{wgtT}, && \text{for spdBV} > \text{spdP} \\ & && \text{and congestion} \\ &= \text{cDis} - \text{wgtS} + \text{wgtT}, && \text{for spdBV} \leqslant \text{spdP} \\ & && \text{and no congestion} \\ &= \text{cDis} - \text{wgtS} - \text{wgtT}, && \text{for spdBV} \leqslant \text{spdP} \\ & && \text{and congestion} \end{aligned} \tag{17}$$

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

5.2.2 *Merging Vehicle Selection - Middle Merge*

In the cases 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 platoonable 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.

5.3 EXPERIMENT

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

1 The 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.

5.3.1 *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 (Figure 16b). 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, overtaking of vehicles is allowed in all lanes not only in the outer lanes. A smooth flow of traffic without a traffic shock has been realized during different merge operations as there are free available lanes and the vehicles can perform lane change and overtake. However, one-two and two-three lane networks are also considered for the testing purpose. In those scenarios, the shock effect is observed in traffic.

The parameters and their values used specific to the simulation are listed in Table 5.

Parameter	Value
Velocity of free vehicle v_0	22 m/s or 25 m/s
Desired velocity of platoon p_0	22 m/s or 25 m/s
Maximum platoon size p_{ms}	20
Buffer length b_{len}	2000 m
Out of reach distance o_{dis}	2000 m
Operation time out t_{out}	180 s
Weight based on comparative speed *wgtS*	0.2
Weight based on surrounding traffic *wgtT*	0.2
Threshold to select merging vehicle *T*	0.6

Table 5: Parameters used in the simulation to analyze different merge operations.

5.3.2 *Performance Metrics*

In this chapter 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 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 (MSR) 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 traffic. In this simulation, two parameters are considered: 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.

5.3.3 *Experimental Results*

5.3.3.1 *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 3 and Table 5. Figure 19 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 17 shows an example of positive distance disFV and negative distance disBV 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 19, the legend names are abbreviated based on the test condition

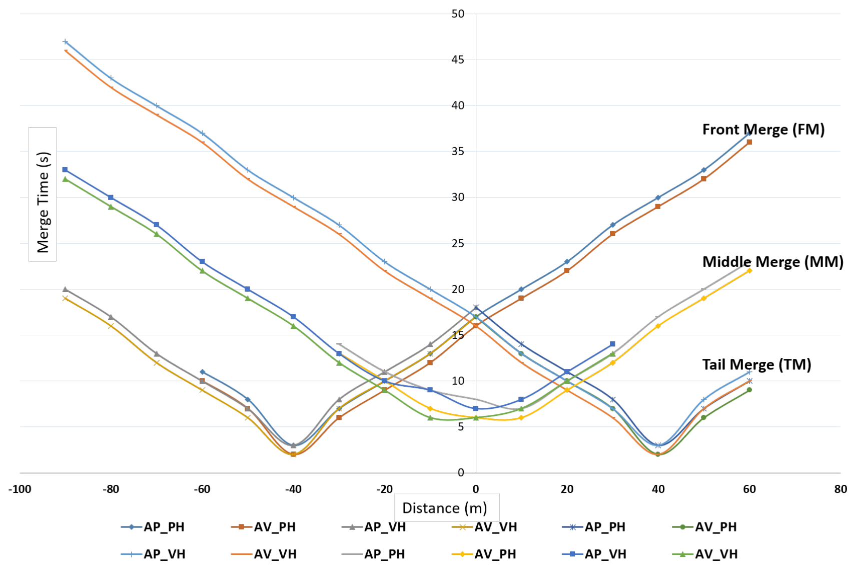


Figure 19: Merge time in the absence of traffic.

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 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.

5.3.3.2 *Experiment 2*

In order to find out the most suitable merge position, the second experiment has been conducted where a vehicle merges in a platoon in different middle positions in the presence of traffic. Three different scenarios are considered as shown in Figure 20. Here circles represent vehicles maintaining their speed, down-arrows represent vehicles slowing down, and up-arrows represent vehicles speeding up. vc_p is the nearest platoon member of merging vehicle vc_m.

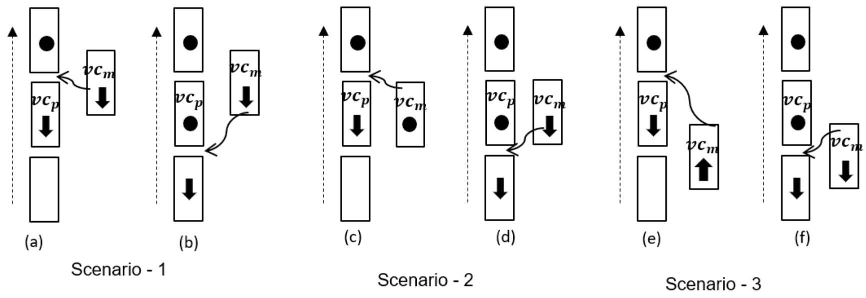


Figure 20: Different options of merge positions in middle merge.

1. *Scenario 1*: The merging vehicle vc_m is ahead of the platoon vehicle vc_p. In Case (a), both vc_m and vc_p can slow down, vc_p creates the gap such that vc_m can take the position of vc_p. Case (b) describes another option, where vc_p maintains its speed such that the following vehicle slows down and vc_m merges behind vc_p.

2. *Scenario 2*: In this scenario, the merging vehicle vc_m is head-to-head with vc_p. In Case (c) vc_p slows down, and vc_m maintains its speed and takes the position of vc_p. Alternatively (Case (d)), vc_p can maintain its speed, and vc_m can slow down and merge behind vc_p.

3. *Scenario 3*: In this scenario, vc_m is in behind of vc_p. One option (Case (e)) is that vc_p slows down and vc_m speeds up and merges in front of vc_p. Case (f): the other option for vc_m is to slow down and merge behind vc_p.

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

5.3.3.3 *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 platoonable. 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 pseudo random 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. 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.

Table 6 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 platoonable. The comparison is shown in Table 7. The Figure 21 shows a graphical representation of the experimental results.

5.4 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 member. It is the most favorable position for tail merge. Also, the merge time is minimum when the

Strategy	Initial platoon length	Final platoon length	MCT per merge (s)	TTD 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

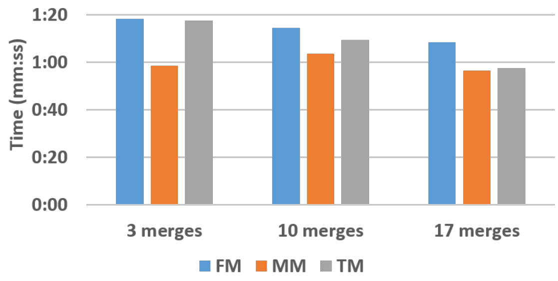
Table 6: Comparison of merge operations in traffic scenario.

Total traffic		MSR	
(Veh/km)	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

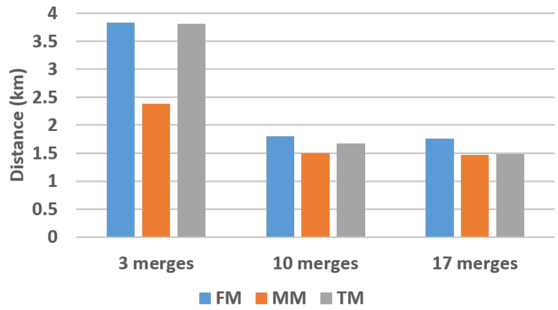
Table 7: MSR of merge operations.

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.

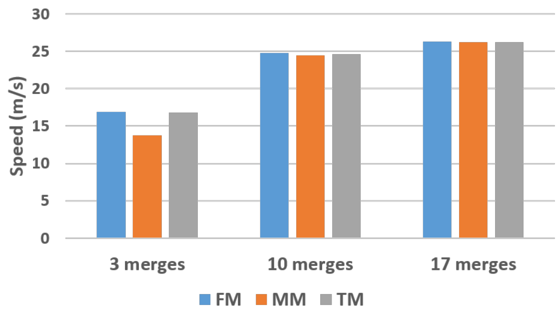
- The pattern of the merge time of front merge is exactly the same as the pattern of the tail merge. For front merge the most favorable scenario is when the vehicle starts 10 m ahead of the platoon leader.
- In middle merge, minimum merge time is 6 s when the merging vehicle is parallel to the middle 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.



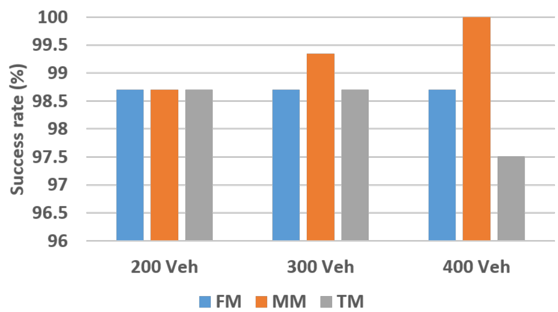
(a) Average time to complete MCT



(b) Total travel distance per vehicle TTD



(c) Average Traffic Speed



(d) Merge Success Rate MSR

Figure 21: MCT, TTD, average traffic speed and MSR in presence of traffic.

- 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. Thus, 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 7 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 a higher success rate in the merge.

- The experiment is conducted for a particular vehicle speed 25 m/s. While a variation of speed, such as 18m/s, 22 m/s, 27m/s leads to an increase or decrease of MCT and TTD, 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. A decrease in speed results in lower MSR. The average traffic speed is not much impacted by speed variation. On the other hand, the increase of the headway or inter-vehicle distance reduces the MCT and TTD. Here also the impact is similar for all there merge operations. Change of the headway has not much impact on MSR or average traffic speed. So, allover the trend of the merge strategies remains the same with the change of parameter values.

5.5 SUMMARY

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.

6 FUEL-EFFICIENT AD-HOC PLATOON FORMATION ON A SINGLE-LANE HIGHWAY

As of the time of writing, the core of this chapter is under review as Maiti, S., Winter, S., Kulik, L. and Sarkar, S (2019). A Strategy of Fuel-efficient Ad-hoc Platoon Formation on a Single-lane Highway. Santa Maiti did this research under the supervision of the co-authors.

The previous chapter already analyzed the flexible platoon merge operations under different traffic and no-traffic scenarios. This chapter analyzes the fuel efficiency of platoons by considering the complete platoon life-cycle from birth to death. The literature and on-road platooning trials typically assume a planned platoon formation at source, and a decomposition of the latoons at the destination. In contrast, this research considers platoons that can be formed in an ad-hoc manner. Then the question arises whether the original benefits of platooning can be preserved for the ad-hoc formations.Hence, for a vehicle it is crucial to decide whether or not to platoon in a given traffic situation. This research aims to solve this decision-making problem by analyzing the situation-aware fuel efficiency of platoon formation and building a cost prediction model. The model provides a guideline of efficient ad-hoc platoon formation.

6.1 INTRODUCTION

Previous studies have shown that platooning can save around 4% of fuel for the front vehicle, and 10% of fuel for the following vehicles for 10 m platoon following distance (Alam, Gattami, and Johansson, 2010; Bonnet and Fritz, 2000; Humphreys et al., 2016; Lammert et al., 2014; McAuliffe et al., 2018; Turri, Besselink, and Johansson, 2016). This fuel saving from platooning is mainly observed from planned formation and decomposition of platoons. In ad-hoc formation, platoons are not generated at a source location or at highway ramps, based on some pre-defined rules. Rather, platoons are generated on the highway out of opportunity, based on platooning interest of the vehicles, their positions, speeds, and destinations. But the fuel advantage of platooning may not be realized if a platoon has to perform frequently merge and split operations, or if the members join the platoon for a short time only. In these cases, the benefits of platooning may not amortize the costs of joining a platoon. Hence, out of all possible opportunities of platoon generation in traffic, only some could be beneficial. Therefore, it is crucial for a vehicle to decide whether or not to platoon in a given traffic situation.

The platoon generation and platoon extension strategies studied so far generally considered merge operations either at highway ramps before entering the highway, or by vehicles entering the highway from a ramp with vehicles traveling already on the highway. In those strategies, vehicles are typically organized into platoons for their common destinations, with the objective of maximizing the travel distance that platoons stay intact. In this case, the costs and the benefits are defined from the outset. In contrast, Hobert allowed the temporary allocation of a vehicle to any available platoon and later, on the highway, the transfer to a more suitable platoon of nearby destination (Hobert, 2012). This strategy makes the platoons unstable. Another prior ad-hoc platoon formation technique (Liang, 2016) performed platoon operations on the highway, disregarding the operational costs of the platoon formation, assuming that these operational costs are negligible compared to the benefits of platooning over long travel distances. But the common travel distances may not always be long. Thus the operational costs should impact the platooning decision.

This research studies scenarios where platoons can be merged or split at any time and new platoons can be formed on the fly. The literature does not provide any guideline towards the selection procedure of platooning vehicles from the traffic but does identify three critical parameters (Liang, 2016) that play an important role to determine the fuel efficiency of platooning, namely the inter-vehicle distance, the distance to the last platoonable point, and the speed difference of merging vehicles. Based on these three parameters this research identifies the vehicles from the traffic that could provide potential fuel benefits from platooning. It does so by proposing a decision model that determines in which scenario the platoons should be formed. To evaluate this decision model the fuel consumption of the vehicles during platooning and non-platooning are compared. Platoons should only be formed if the total fuel consumption is lower when platooning.

Hypothesis: A guided way of ad-hoc platoon formation preserves platooning benefits compared to the free-flow traffic (and thus with opportunistic ad-hoc platoon formation). The support for this hypothesis can also suggest a guideline for the choice of platooning vehicles and platooning strategy in a given traffic scenario.

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

1. *Selection of vehicles for platooning having potential fuel benefit* - In traffic, there could be many possibilities of platoon formations from any number of given vehicles, and these possibilities could also conflict with each other. All of the formation attempts may not succeed. A merge operation may succeed or fail based on the vehicle's position and the surrounding traffic. For example, if the distance between two vehicles is high, catch up may not

possible. Alternatively, if the merging vehicle's surrounding traffic density is high, the platoon formation may fail. A failed attempt comes with costs of higher fuel consumption than traveling without the platoon attempt. Thus, it is important to decide *a priori* which vehicles could try to form platoons and which vehicles should better travel independently.

2. *A decision model that recommends vehicles to form fuel-efficient platoons* - Among all the possibilities of platoon formation, some pairings take shorter and some take longer execution times to form the platoon. The execution time, with its acceleration and deceleration patterns, has an impact on the fuel costs of platoons. This is termed as execution *overhead*. In some cases, the fuel cost for the overhead exceeds the platooning benefit. As there are many possibilities for allocating vehicles to platoon groups, it is not feasible to analyze the cost-benefit ratios for all possible combinations in order to find the optimal one. Therefore, this research builds a decision model to recommend vehicles and a strategy of fuel-efficient platoon formation.

Thus, the objective of this chapter is to develop a decision-making system that recommends platoon formation in given traffic. In order to deal with combinatorial complexity, this chapter limits itself to single-lane highway traffic, later the insights are translated into more complex situations of multi-lane traffic. Single-lane highway traffic restricts the platoon formation to front or tail merge and excludes middle merge (Maiti, Winter, and Kulik, 2017) and overtake. In spite of the simplification, the experimental setup is sufficient enough to test the proposed model's robustness for decision-making in a given traffic situation. The research will lead to these key contributions:

1. A selection of platoonable vehicles out of the traffic that provides potential fuel benefit.
2. A prediction model of fuel efficiency based on the inter-vehicle distance, the distance to the last platoonable point, and the speed difference of vehicles.
3. A demonstration and validation of real-time use of the decision model to generate and maintain platoons in a fuel-efficient way.

In this chapter, Section 6.2 describes the proposed methodology. Section 6.3 demonstrates the experiments and experimental results. An analysis of the experimental results and the key insights are presented in Section 6.4. Section 6.5 summarizes this chapter.

6.2 PROPOSED METHODOLOGY

The life-cycle of a platoon can be represented by three different phases, namely platooning vehicles' selection from free-flow traffic, platoon formation, i.e., the birth of a platoon and incremental growth by consecutive merge operations, and platoon dissolution, i.e., membership reduction, rebuild of platoon, and death of a platoon as shown in Figure 22.

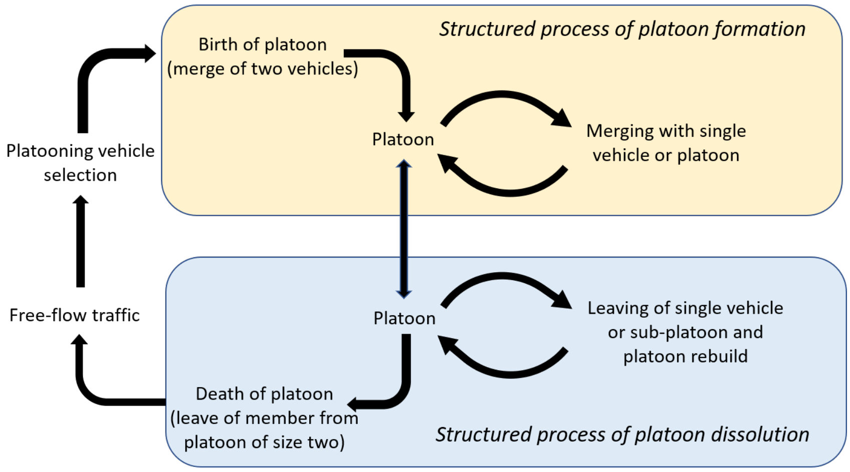


Figure 22: The life-cycle of a vehicle platoon.

The important aspect of this chapter is to provide a situation-aware guideline whether a vehicle should join a platoon and what could be the formation strategy. To fulfill the aim, this research proposes a methodology as shown in Figure 23.

The proposed model has three main modules that includes, 1) the feature value extraction of vehicles, 2) the decision model to decide which vehicles should participate in platooning, and 3) the platooning model to generate platoons. Later, the fuel consumption of vehicles that form platoons is calculated and compared with the fuel consumption of the same vehicles, when non-platooning. A correct decision should show fuel savings from platooning.

6.2.1 *Feature Value Extraction*

In the first module of feature value extraction, the three important parameters that play a key role in the decision of platooning are identified. The parameters are: the inter-vehicle distance that indicates the inter-between distance of two vehicles, the last platoonable point distance that indicates the maximum distance the vehicles can travel as a platoon, and the speed difference of the vehicles. In this module, the free-flow traffic is considered as the input and the values of these three parameters of all vehicles are obtained. Also, the positions of the vehicles are noted. In the next module, the decision of platooning is taken based on all these parameter values.

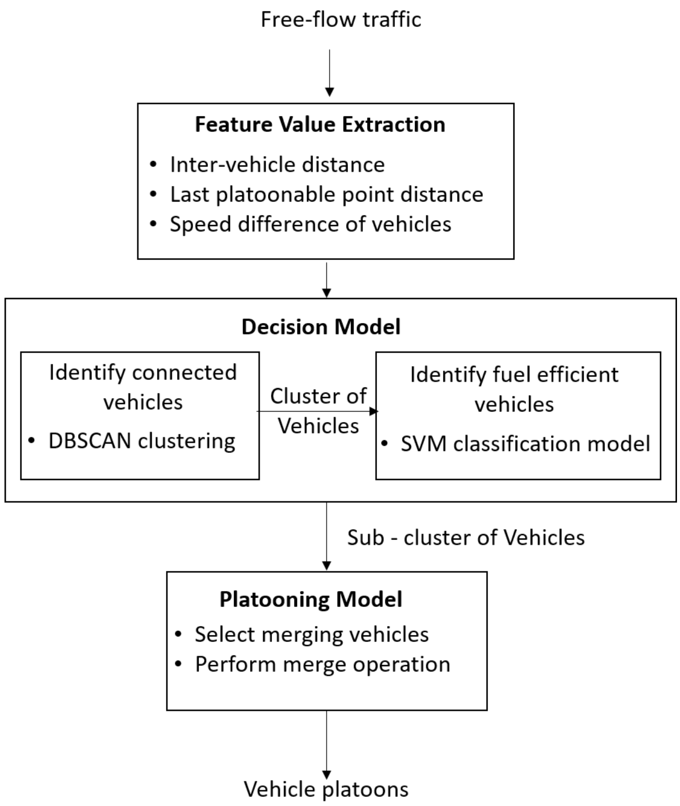


Figure 23: Block diagram of ad-hoc platoon formation.

6.2.2 *Decision Model*

The aim of this decision model is to identify vehicles that can provide potential fuel benefit while platooning. To achieve this, the decision model is further divided into two sub-modules.

6.2.2.1 *Identify the connected vehicles*

The first sub-module identifies the connected vehicles that are in communication range and can 'talk' with each other for co-ordination. For this purpose, the vehicles are clustered based on their position. Here, the density-based clustering algorithm DBScan (Ester et al., 1996) is used. The application of the clustering algorithm results in lists of connected or clustered vehicles.

6.2.2.2 *Identify the fuel-efficient vehicles*

Not all the vehicles of a cluster may find joining in a single platoon beneficial. For example, the merge of the first vehicle and the last vehicle of a cluster may not be beneficial. In the second sub-module of the decision model, the clustered vehicles obtained from the previous step are further partitioned into sub-clusters so that the platoon formed with the vehicles of a sub-cluster can provide fuel benefit. Hence, the question becomes how to ensure the merge operations of the vehicles of a sub-cluster will be fuel-efficient? The fuel efficiency of platooning depends on the key parameters - the inter-vehicle distance, the distance to the last platoonable point, the speed difference of merging vehicles and also the speed adjustment of the vehicles. As the parameter values vary widely, it is difficult to provide an analytical decision on fuel efficiency for any given traffic scenario. Hence, This research uses Support Vector Machine (SVM) classification model to take the decision. Before using the SVM classifier as a decision model, the training of the classifier is needed. The training data is prepared by simulating two vehicles. The training module is shown in Figure 24.

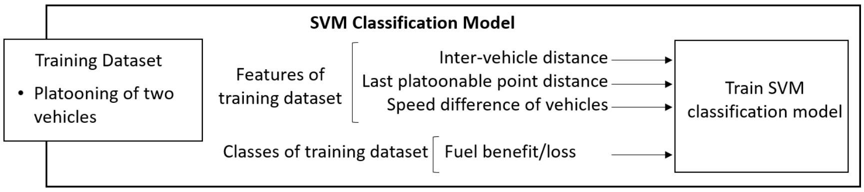


Figure 24: Training of the SVM model.

TRAIN SVM MODEL To generate the training data, this research performs *basic platooning* with two vehicles using the following steps.
Step 1: Two vehicles are initialized in the given highway network N having entry and exit ramps, with a route R and an initial inter-vehicle distance d_0.
Step 2: The platooning vehicles' speed v is set.
Step 3: Among the two platooning vehicles, the preceding vehicle slows down and the succeeding vehicle maintains its speed to reduce the inter-vehicle gap.
Step 4: Once the inter-vehicle distance is near to the desired intra-platoon gap h, the preceding vehicle speeds up to achieve the succeeding vehicle's speed to form a platoon. Once the platoon forms, both vehicles start moving with speed v to keep the constant intra-platoon gap.
Step 5: The simulation runs until one of the platooning vehicle exits from the highway.
The platooning vehicles' fuel consumption F_p is computed according to the fuel consumption model mentioned in Section 4.3. These vehicles are again simulated with the same initial condition; this time vehicles move freely as per the IDM model without making platoon. The fuel consumption of non-platooning f_{np} is also computed. The difference between F_p and F_{np} is considered as fuel benefit or loss.

This basic model runs with systematic variations of d_0, R, and v. These parameters are considered as the feature set and fuel benefit and loss are considered as classes and used to train the SVM classification model. The model learns the parameter combinations where platooning is efficient.

TEST SVM MODEL After training, the SVM model is used for decision making in the next platooning module. Based on the inter-vehicle distance, the last platoonable point distance, and the speed difference value obtained in feature value extraction phase, the SVM model predicts if the merge of two vehicles of a cluster will be fuel-efficient or not. If the model predicts the merge will be fuel-efficient, then both vehicles are assigned to the same sub-cluster. Otherwise, the vehicles are assigned to different sub-clusters. It might be also possible a vehicle has no fuel benefit from platooning. Such a vehicle is not assigned to any of the sub-clusters. From a vehicle cluster, one or more sub-cluster(s) can be generated.

6.2.3 *Platooning Model*

Once the sub-clusters are identified, from each sub-cluster a platoon is generated. The formations of platoons are performed in parallel. From each sub-cluster, two vehicles are selected for the first merge operation. The merge results in a platoon of two vehicles. In the next iterative steps, the nearest vehicle to the platoon is selected to perform merge operation. Once platoon formation is completed, the platoon travels as per the designated route.

Ad-hoc platoon formation and decomposition: The detailed steps of ad-hoc platoon formation and decomposition are described in Algorithm 6. The variables and the parameters used in the algorithm have the following meaning.

- T is the traffic consist of free flow vehicles
- $C = \{C_1, ...C_n\}$ is the clusters of vehicles
- SC is the sub-clusters of a clustered vehicles
- $VC = \{vc_1, ..vc_m\}$ is the ordered vehicles of a sub-cluster
- P is the platoon consist of vehicles
- $nVeh$ is the suitable merging vehicle
- $spdP$ is the next level platoon speed
- $spdV$ is the next level merging vehicle speed
- F_p is the fuel consumption of platooning vehicles
- N is the simulation network
- R is the route of the vehicles

- v is the desired speed of free flow vehicle and platoon
- PP is the platoon pool

Step 1: The traffic is initialized randomly on the highway and through the entry ramps of the network N. The vehicles' destinations, i.e., the exit ramps, are also randomly distributed. The traffic is initialized with the desired speed v (line 2).
Step 2: The DBScan clustering algorithm is used to cluster vehicles based on vehicles' position on the road network. Each cluster contains the vehicles that are within the communication range of their radio, i.e., vehicles that are connected and can collaborate (line 3).
Step 3: The next step is to identify sub-clusters SC of vehicles. Initially, SC is empty (line 5).
Step 4: For each cluster, vehicles are ordered $VC = \{vc_1, vc_2, \ldots, vc_m\}$ based on their position (line 6). Here, the vehicles vc_3 and vc_1 are the preceding and the succeeding vehicles of vc_2, respectively.
Step 5: The last vehicle towards the movement direction, vc_1, is identified (line 8).
Step 6: Next, from the ordered vehicles, the vehicle vc_k is identified such that the platoon of vc_1 and vc_k is fuel-efficient and the platoon of vc_1 and vc_{k+1} is not fuel-efficient (line 9). For this prediction, the trained SVM model is used. The model takes the merging vehicles' current gap, the distance of last platoonable point and the speed difference of merging vehicles as the input and predicts if the merge will be fuel-efficient or not. Therefore, if a platoon is generated with vehicles $vc_1, vc_2, \ldots, vc_k$, there will be a possibility of fuel saving compared to the non-platooning scenario. Point to note, after deciding a merge of two vehicles is fuel-efficient, when the next merge operation is tested, the expected travel distance of the first merge is deducted from the last platoonable point distance of next merge to obtain the remaining platooning distance.
Step 7: Vehicles $vc_1, vc_2, \ldots, vc_k$ are identified as the first sub-cluster. These selected vehicles are removed from the vehicle set (line 10-12). This process repeats to identify all sub-clusters of vehicles of all clusters.
Step 8: The sub-clustered vehicles merge to generate platoons (line 15-41). From a sub-cluster the first two vehicles are selected for the first merge. One vehicle is assigned as initial platoon P (line 17) and the other one is assigned as merging vehicle *nVeh* (line 23). The merge results in a platoon of length two. Again, the next merging vehicle *nVeh* is selected from the sub-cluster. The process repeats until all the vehicles of the sub-cluster complete the merge and form a single platoon.
Step 9: The generated platoons from sub-clusters travel along the highway. In each iteration, the simulation tests if any member of the platoon reaches its destination ramp (line 44). If any such member is identified, the platoon performs a split operation (line 45) and the

Algorithm 6: Ad-hoc Platoon Formation and Decomposition

```
Input: network N, route R, desired flow speed v
Output: total fuel consumption F
begin
    T ← InitializeTraffic(N, R, v)
    C = {C1, C2, ..., Ci, ..., Cn} ← GetConnectedVehicles(T)
    for each Ci ∈ C do
        SC = ∅
        VC = {vc1, vc2, ..., vcm} ← GetOrderedVehicles(Ci)
        while !Empty(VC) do
            vc1 ← GetLastVehicle(VC)
            vck ← FindFuelEfficientVehicle(VC), such that vck is fuel
              efficient, vck+1 is not fuel efficient
            SCj = {vc1, vc2, ..., vck}
            VC = {vck+1, ..., vcm} ← SetDifference(VC, SCj)
            SC = Append(SC, SCj)
        end
    end
    for all Ci ∈ C do
        for all SCj ∈ Ci do
            P ← SelectInitialPlatoon(SCj)
            SCj ← SetDifference(SCj, P)
            isOperationalState(P) = False
            while !isEmpty(SCj) do
                if !isOperationalState(P) then
                    if isEmpty(nVeh) then
                        nVeh ← FindMergingVehicle(SCj)
                        SCj ← SetDifference(SCj, nVeh)
                        isOperationalState(P) = True
                    endif
                endif
                else
                    if isMerged(P, nVeh) then
                        SetDesiredSpeed(P, v)
                        isOperationalState(P) = False
                    endif
                    else
                        spdP ← SetNextLevelSpd(P)
                        spdV ← SetNextLevelSpd(nVeh)
                        P ← Merge(P, nVeh, spdP, spdV)
                    endif
                endif
            end
            PP = Append(PP, P)
        end
    end
    for all Pi ∈ PP, Size(Pi) >1 do
        vcx ← GetLeavingVehicle(Pi)
        Split(vcx, Pi)
        if isMiddleMember(vcx) then
            Rebuild(Pi)
        endif
    end
    Fp ← CalculateFuelConsumption(PP)
end
```

vehicle exits through destination ramp. If the member leaves from middle position, the platoon is rebuilt (line 46-48).
Step 10: The platooning vehicles' fuel consumption is computed according to the fuel consumption model (line 50).
The complete simulation is repeated with the same initial condition, without platooning. The fuel consumption of the vehicles during non-platooning is compared with the fuel consumption during platooning to validate that the platooning decision is fuel-efficient. The result indicates the accuracy of the proposed model.

6.3 EXPERIMENT

The car-following models and the fuel consumption model described in Chapter 4 are used for the experiments. In this research, a vehicle decides to platoon or not based on its potentiality of fuel efficiency from platooning. On highway, aerodynamics influences a vehicle's fuel consumption significantly. The aerodynamic drag works as a resistive force due to the interaction between the vehicles and the surrounding air. It has a strong impact with higher velocity and can account up to 50% of the total resistive force at full speed. On-road trials have already shown that the air drag resistance can be reduced by aligning vehicles close behind each other in a platoon. Hence, it is important to consider a fuel consumption model that accounts the effect of aerodynamic resistance.

The follower vehicle experiences a significant reduction in air drag resistance due to the lowered pressure at its front. The lead vehicle also experiences a reduced air drag if the follower vehicle drives close enough to dissolve the turbulent wake that occurs behind a vehicle. The amount of air drag on the lead vehicle and the follower vehicle is represented by the air drag ratio. The value of the drag ratio is considered as 0.9 for platoon leader and 0.6 for platoon follower for 10 m inter-vehicle distance (Liang, 2016). This research assumes that all the platoon followers experience the air drag ratio for simplification. In reality, the followers at the back-end experience lower air drag with respect to the followers at the front. This assumption increases the fuel consumption of a platoon in some percentage for a platoon of length three or more, but not exaggerate about platoon's fuel benefit. Along with the air drag ratio, the aerodynamic force on a vehicle also depends on the vehicle's speed. Hence, if the vehicles move as a platoon at high speed for longer distance, a significant fuel benefit can be achieved compared to the vehicles traveling alone.

6.3.1 *Simulation Setup*

To simulate the platoons and the traffic and to evaluate the fuel consumption in platooning and non-platooning scenarios, a 40 kilometer long straight highway traffic network is designed. The network consists of 20 segments of 2 km length each. In each segment, there is an entry ramp and an exit ramp. In this chapter, the experiment is limited to a single lane highway which will restrict any vehicle to overtake. The parameters and their values used in the platoon simulation and in the fuel consumption model are listed in Table 3, Table 8, and Table 4.

Parameter	**Value**
Desired velocity of platoon and free vehicle v	28 m/s
Neighborhood distance in DBScan d'	300 m
Minimum vehicles required to form a dense region $minPts$	2

Table 8: Parameters used in the simulation to form fuel-efficient platoons.

6.3.2 *Performance Metric*

The aim of this research is to identify if an ad-hoc manner of platoon formation is beneficial or not. Hence, two metrics are used, namely, fuel saving, and prediction accuracy for evaluation purpose.

1. *Fuel saving*: This research uses fuel consumption as an evaluation metric. An instantaneous fuel consumption model described in Section 4.3 is used to compute the fuel consumption of vehicles both for platooning and non-platooning. The difference of fuel consumption while non-platooning and platooning is considered as fuel saving and expressed in terms of percentage.
2. *Prediction accuracy*: Prediction accuracy is another measure used to evaluate the proposed decision model. It is calculated as the percentage of correct prediction to form fuel-efficient platoons, out of all predictions. Here, the accuracy of prediction implies if the whole platoon will be fuel-efficient or not. The fuel-efficiency of an individual member is not considered here.

6.3.3 *Experimental Results*

6.3.3.1 *Experiment 1*

The first experiment of basic platooning is conducted to generate the training data and to train the SVM classification model by varying the platooning parameters: the initial inter-vehicle distances, the last platoonable point distances, and the speed difference of merging vehicles. Here, only two vehicles are used for platooning.

- *Inter-vehicle distance variation:* The succeeding vehicle, vc_s, is placed at the start of the first segment of the highway. The preceding vehicle, vc_p, is placed in front of vc_s at a certain distance d_0. d_0 varies from 40 m to 300 m. The minimum value of d_0 is considered as 40 m to avoid the collision when the vehicle travels at 28 m/s speed (the safe distance). The maximum distance is chosen as 300 m as vehicle-to-vehicle technology uses dedicated short-range communications (DSRC) that ranges up to 300 m (Bai, Stancil, and Krishnan, 2010): beyond this distance vehicles cannot collaborate directly. Figure 25 shows the initial inter-vehicle distance d_0.

- *Last platoonable point distance variation:* The exit ramp of the succeeding vehicle, vc_s, varies between the first ramp, which is 2 km ahead, and the twentieth ramp, which is 40 km ahead. Therefore, the last platoonable point d_p varies from 2 km to 40 km respectively. The last platoonable point distance d_p is also shown in Figure 25.

- *Speed variation:* The speed of the vehicles are varied from 16 m/s to 28 m/s which is the maximum and minimum vehicle speed limit set in this simulation.

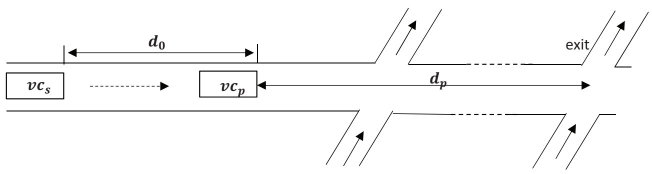


Figure 25: Inter-vehicle distance and last platoonable point distance.

During the merge operation vehicles follow the same speed dynamics. Vehicles can accelerate 1 m/s^2 or decelerate 4 m/s^2. This research assumes in any traffic condition a vehicle or a platoon travels with its maximum speed 28 m/s on highway unless the speed is impeded by the preceding vehicles. Under this assumption, it is not possible for the following vehicle to speed up and catch the preceding vehicle to form a platoon. Hence, this research considers that the preceding vehicle reduces its speed minimum up to 16 m/s, which is assumed as the minimum speed to maintain at highways[1,2] to merge with the following vehicle. This particular design choice allows that platoons in principle can travel with maximum legal speed – no catching-up vehicle has to go beyond legal speed limits.

1 Speed limits in Australia, https://en.wikipedia.org/wiki/Speed_limits_in_Australia, accessed on Nov 18, 2018

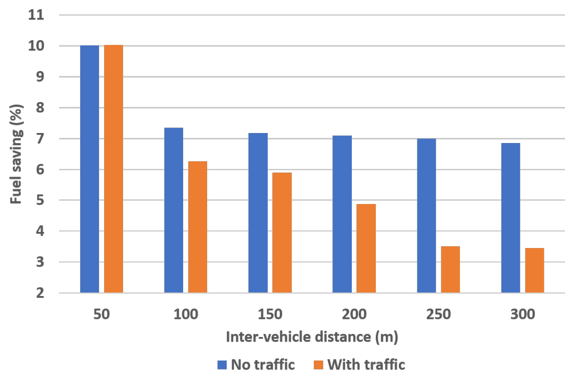
2 Speed limits in the United States by jurisdiction, https://en.wikipedia.org/wiki/Speed_limits_in_the_United_States_by_jurisdiction, accessed on Nov 18, 2018

All the simulation results, i.e., fuel benefits or losses with the variation of input parameters, are recorded. This recorded data is then used for training the SVM model. 80% of the randomly chosen data is used for training purpose. Remaining 20% data is used to validate the model's correctness. It shows 96.41% prediction accuracy of the proposed model.

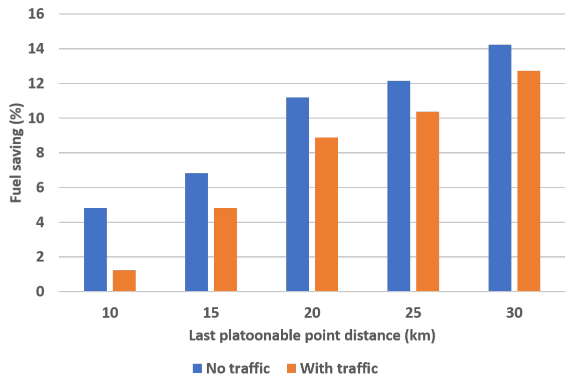
6.3.3.2 *Experiment 2*

In the second experiment, platoons are formed from the traffic. This experiment considers the traffic of ten vehicles per km. Vehicles are randomly initiated all over the network. Also, a flow of 360 vehicles per hour is initiated through the entry ramps to add some disturbances in the traffic. Total 30 testcases are considered to form and dissolve platoon in ad-hoc manner. During the formation, the connected or clustered vehicles are identified by applying the density-based DB-Scan clustering algorithm. The value of neighborhood distance d' is set to 300 m, the same as the DSRC range of communication. The minimum number of points ($minPts$) required to form a dense region is decided as 2, as at least two vehicles are needed to form a proper platoon. This clustering algorithm is executed in a 10-sec-interval to check if the cluster remains the same or any changes happened as a new vehicle enters in the cluster or a vehicle moves out from the cluster.

All the vehicles of a cluster are further sub-clustered to identify fuel-efficient vehicle groups. The vehicles in a sub-cluster merge and form a single platoon. Therefore, from n sub-clusters, n numbers of platoons are expected. Once the probable platooning vehicles and corresponding platoons are identified, the speed of platoon members is adjusted to form platoons. The rest of the non-platoonable vehicles moves freely as per the IDM model. These vehicles may impact on platoon formation. The platoons move along the highway until the member vehicles exit through ramps. If a middle member of a platoon needs to exit through the ramp, the platoon allows the member to exit and rebuilds again. The fuel consumption of the platooning vehicles is calculated both for platooning and non-platooning scenarios, with the same initial condition. Finally, the fuel saving is analyzed with respect to inter-vehicle distances, last platoonable point distances and platoon sizes. Also, prediction accuracy is calculated to validate the decision model. Figure 26a shows the variation of average fuel saving for platoon size two with respect to initial inter-vehicle distances. Here, the platoon travels twelve km on an average without and with traffic. Similarly, Figure 26b shows the variation of average fuel saving for platoon size two with respect to last platoonable point distances. Here, the initial inter-vehicle is 150 m on average and both without and with traffic scenarios are compared.



(a) Fuel saving with respect to inter-vehicle distances



(b) Fuel saving with respect to last platoonable point distances

Figure 26: Fuel saving with respect to inter-vehicle distances and last platoonable point distances.

Figure 27 shows the variation of average fuel saving with respect to platoon size and last platoonable point distances. Here, the fuel savings is in average per vehicle in the platoon including the platoon leader. The average inter-vehicle distance is 60 m.

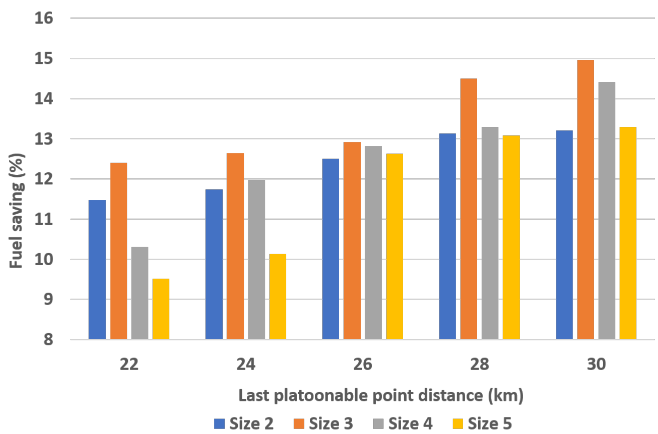


Figure 27: Fuel saving based on platoon size.

6.4 DISCUSSION

This section presents an analysis of the observed results.

- The fuel saving graph presented in Figure 26a shows that the fuel saving is higher for lower inter-vehicle distances and lower for higher inter-vehicle distances.
- Without traffic, the fuel saving is higher for inter-vehicle distance 50 m to 100 m. In this scenario, the preceding vehicle reduces its speed maximum to minimum possible speed and complete the merge process quickly. Whereas, in the scenario of inter-vehicle distances 100 m to 300 m, the fuel saving percentage is slowly decreasing. Here, the preceding vehicle can not reduce its speed beyond 16 m/s. Therefore, the fuel saving not varies much. In traffic, the merge operation is delayed due to the presence of other vehicles. The fuel saving is inversely proportional with inter-vehicle distance. It implies when inter-vehicle distance increases the fuel saving decreases.
- For lower inter-vehicle distance the fuel saving is more or less same with or without traffic. Whereas, the fuel saving is impacted by traffic for higher inter-vehicle distances.
- The fuel saving graph presented in Figure 26b shows that the fuel saving increase with respect to the last platoonable point distances. It indicates the more distances the vehicles move together, more fuel saving can be obtained.
- The fuel saving percentage is more impacted by the last platoonable point distance compared to the inter-vehicle distance as, the range of inter-vehicle distance is less compared to the range of last platoonable point distance.
- Figure 26b also shows that the traffic has a lesser impact on fuel saving when the last platoonable point distance is high.
- The fuel saving graph presented in Figure 27 shows that for a particular platoon size, the percentage of fuel saving increases with the last platoonable point distances.
- For platoon sizes of three or four vehicles, higher fuel saving can be obtained on average. For platoon size five, the fuel saving percentage is reduced as the vehicles leave from the middle of the platoon and the platoon rebuild results in extra fuel expenditure.
- For platoon size four and five, the fuel saving percentage is less for shorter travel distances as formation and decomposition takes more fuel rather than fuel saving from the platooning.

- The experimental result shows 89.2% prediction accuracy of the proposed model to form fuel-efficient platoons while considering the traffic. The prediction accuracy drops compared to the training phase as the training phase does not consider the traffic. Moreover, the SVM model is trained with platoon size 2, therefore, the platoon rebuild cost due to the leaving of the middle member is not considered in the training phase.

- A sensitivity analysis is conducted to realize how the prediction accuracy is impacted by the change of the two parameters of DBScan, namely neighborhood distance and minPts. Experiment 2 considers the values of the neighborhood distance and minPts and 300 m and 2, respectively. When the neighborhood distance is reduced to 100 m, it results in smaller platoon size and that increases prediction accuracy to 92.7%. Whereas considering neighborhood distance as 500 m increases platoon size on an average. As a result, the prediction accuracy drops to 82%. Changing minPts > 2, forces to build platoon of size greater than 2. It also reduces the prediction accuracy.

- The research also tested how the prediction accuracy is impacted by the change in traffic density. Experiment 2 considers a traffic density of 10 vehicles per km. For a lower traffic density of 6 vehicles per km the vehicles need to travel longer to build the platoon, but the formation process is less impacted. It results in comparatively lower fuel advantage (in a range of 1% - 1.8%) and higher prediction accuracy (91%). On the other hand, for a higher traffic density of 12 vehicles per km, vehicles are closer to each other and can catch up easily for formation. But in this case, the formation is impacted by the dense traffic. So, on average, the prediction accuracy drops (84%) but the successful prediction increases the fuel efficiency (in a range of 2.5% - 4%).

- This research considers heavy duty trucks for platooning and computes the potential fuel benefit for this vehicle type. Therefore, a standard weight of truck/trailer has been considered and corresponding cross-sectional area are considered for the calculation of fuel consumption. However, in the fuel model, the fuel saving due to the air drag reduction is not directly related to vehicle mass. Hence, the fuel saving percentage does not differ much based on the vehicle mass when other parameters are unchanged.

The platoons can be generated in many possible ways from given traffic. This research does not investigate all possible ways of platoon formation and corresponding fuel efficiency. The proposed methodology proposes a heuristic of applying clustering algorithm and classification model to provide a strategy of platoon formation and dissolution.

6.5 SUMMARY

This research investigates first the basic platooning of two vehicles in the absence of traffic by varying the platooning parameters of inter-vehicle distance, last platooonable point distance, and the speed difference of vehicles. For these three parameters fuel benefits were observed and recorded. In the next step, this recorded data is used to train a SVM classification model. In the final step of this research, platoons are generated from randomly distributed traffic in an ad-hoc manner. The DBScan algorithm is used to identify the vehicles that are within radio range from each other and thus can co-ordinate for ad-hoc platoon formation. The trained SVM model is used to identify the vehicles that have potentially a fuel benefit from platooning. Applying these decision rules, the experimental results show the accuracy of the prediction model. This experiment uses a specific speed profile and acceleration, deceleration pattern of the vehicles. However, for a different speed profile and acceleration, deceleration pattern the same methodology of training can be used to build the decision model.

In general, a platoon obtains higher fuel saving for lower inter-vehicle distance and higher the last platoonable point distance. Traffic has a lesser impact on fuel saving for lower inter-vehicle distance and higher the last platoonable point distance. For the platoons of three or four vehicles, higher fuel saving can be obtained on average. For higher platoon size, the fuel saving percentage is reduced as the vehicles leave from the middle of the platoon and the platoon rebuild results in extra fuel expenditure. For longer platoon, the fuel saving percentage is less for shorter travel distances as formation and decomposition take more fuel rather than fuel saving from the platooning.

Overall the research presents a decision-making model that recommends a fuel-efficient way of platoon formation. The experimental results prove that a guided way of ad-hoc platoon formation can preserve the platooning benefit compared to the free-flow traffic. The research contributes towards the real-time selection of platooning vehicles to generate and maintain the platoon in a fuel-efficient way.

7 AD-HOC PLATOON FORMATION AND DISSOLUTION STRATEGIES ON A MULTI-LANE HIGHWAY

A part of this chapter has been published as Maiti, S., Winter, S., Kulik, L. and Sarkar, S (2019). Analysis of an Ad-hoc Platoon Formation and Dissolution Strategy on a Multi-lane Highway. 15th International Conference of GeoComputation 2019.

A significant extension of the previous chapter is under review as Maiti, S., Winter, S., Kulik, L. and Sarkar, S (2019). Greedy and Order-based Ad-hoc Platoon Formation and Dissolution Strategies on a Multi-lane Highway. Santa Maiti did the research under the supervision of the co-authors.

This research proposed a decision model in the previous chapter that guides towards fuel-efficient ad-hoc formation and dissolution of the platoons. However, the simulation is restricted to single-lane highway to reduce the combinatorial options of platoon formation. In this chapter, the research enables the multi-lane highway that allows the vehicles to move freely and to form platoons. This chapter investigates two types of ad-hoc platoon formation and corresponding platoon dissolution strategies. The first approach forms a platoon greedily without considering the order of destinations of the platoon members. This approach enables a quick formation but imposes an overhead of platoon rebuilding, and consequently, additional fuel cost when platoon members leave. An alternative approach forms a platoon in the order of the destinations of its platoon members. This ordered approach incurs a comparatively higher formation time due to vehicles' reorganization but does not lead to further overhead of platoon rebuilding. The research investigates whether these ad-hoc formation and dissolution strategies can preserve the original fuel benefit of platooning, and which of the two ad-hoc formation strategies are more fuel-efficient.

7.1 INTRODUCTION

A multi-lane highway provides opportunities for a lane change, speed adjustment and rearrangement of vehicles. Therefore, the platoons can be formed in many different ways: based on the destination order, with a destination range constraint, or randomly. The benefits of these different strategies may also differ. For example, the speed adjustment of vehicles during platoon operations may lead to additional fuel consumption impacting on the fuel benefit of being a platoon. Therefore, it is necessary to analyze ad-hoc platoon formation and dissolution strategies and their corresponding fuel consumption.

This chapter analyzes two types of ad-hoc platoon formation strategies, namely a greedy platoon formation and an ordered platoon formation. These are two different types of strategies; one considers the fast and easy platoon formation and the other considers fast and easy platoon dissolution. In the greedy formation, the vehicles are organized based on their current position irrespective of their destination. This strategy does not involve vehicle rearrangement. Thus, lesser vehicle movements are required during the formation compared to the ordered formation. In this strategy, less formation time and fuel consumption are expected. But due to the random order of the destinations, upon arrival at a destination ramp members may leave the platoon from any position, also from the middle. Hence, the platoon needs to be rebuilt with the remaining vehicles, which impacts on the overall fuel benefit of the platoon. The alternative formation strategy is the ordered formation. Here, the vehicles are organized based on their destinations of the platoon members either in ascending or in descending order. This strategy involves more vehicle movement, more operation time, and hence, higher fuel consumption during platoon formation. Upon arrival at the destination ramp, the members always leave the platoon from the front or back, free of cost for the rest of the platoon. Hence, the platooning benefit remains intact. As both formations have some positive and negative impacts, this research implements and evaluates the formation strategies in the simulation environment to determine which strategy outperforms in a given traffic scenario.

Hypothesis: The greedy ad-hoc platoon formation-dissolution strategy outperforms an ordered ad-hoc formation dissolution strategy in multi-lane highways.

It is clear that there will be only limited support for the hypothesis. Thus analyzing the support for this hypothesis collected in an experiment will allow us to suggest guidelines for the choice of a formation strategy in a given traffic situation. Towards fulfilling this research objective, the key contributions will be:

1. Modeling and implementing the greedy and the ordered platoon formation and dissolution strategies on a multi-lane highway;
2. An analysis of the fuel efficiency of the proposed formation and dissolution strategies;
3. A guideline for the choice of a formation strategy in a given traffic situation.

Section 7.2 describes the proposed models of ad-hoc formation and dissolution strategies. Section 7.3 illustrates the proposed strategies in a simulation environment. Section 7.4 shows the experiments and their results. The observations from the simulation and the key insights are presented in Section 7.5. Section 7.6 summarizes the chapter.

7.2 PROPOSED METHODOLOGY

In the previous chapter it is realized that not all vehicles can obtain fuel benefits from platooning. Hence, it is crucial to identify only those vehicles from the traffic that can obtain potential fuel benefits from platooning. Thus, before applying the formation strategies, the suitable candidates for platooning are identified using the same process mentioned in the previous chapter. The process includes the modules of feature value extraction, identification of the connected vehicles, and identification of the fuel-efficient vehicles.

7.2.0.1 *Ad-hoc Platoon Formation*

Once platooning vehicles are selected, their speeds are adjusted to form platoons. Out of the possible ways of platoon formation from the sub-clustered vehicles, this research models and implements two disparate strategies:

1. *Greedy formation*: In this formation strategy, a platoon is formed only based on the longitudinal positions of sub-clustered vehicles. Once a sub-cluster is identified, the vehicles' positions are compared. 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: The vehicles first change their lane 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.
   Step 3: If two vehicles are exactly in the same position, then the vehicle with the nearer destination slows down.
   Step 4: After all vehicles of the sub-cluster are moved to the same lane, the formation process starts.
   Step 5: The first pair of vehicles are selected. From the pair, the preceding vehicle slows down and the succeeding vehicle maintains its speed to reduce the inter-vehicle gap.
   Step 6: 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. This is the birth of a platoon.
   Step 7: Next, from the sub-cluster the nearest vehicle to the

platoon is identified to merge with the platoon. The platoon slows down to perform the back merge operation. The process repeats until all the vehicles of the sub-cluster merge and form a single platoon.

2. *Ordered formation*: In ordered platoon formation, the vehicles of a sub-cluster are organized to form a platoon based on their destination.
Step 1: From the destinations of all vehicles of the sub-cluster, the unique destinations are identified.
Step 2: The unique destinations are sorted from farthest to nearest.
Step 3: For each unique destination, the set of possible combinations of vehicles are found. For example, let there be two vehicles vc_1, vc_2 of destination d_1, and two other vehicles vc_3, vc_4 of destination d_2. Then there are two possible combinations of vehicles for d_1: (vc_1, vc_2) and (vc_2, vc_1). For d_2 also there are two possible combinations: (vc_3, vc_4) and (vc_4, vc_3).
Step 4: Next, all destinations in descending order are considered to obtain the complete set of all possible combinations of vehicles. For the above example, if d_1 is nearer than d_2, then the all possible combinations of the vehicles are (vc_1, vc_2, vc_3, vc_4), (vc_2, vc_1, vc_3, vc_4), (vc_1, vc_2, vc_4, vc_3), (vc_2, vc_1, vc_4, vc_3).
Step 5: The possible combinations of vehicles for the reverse (ascending) order of destinations are also obtained. For the above example, these combinations are (vc_4, vc_3, vc_2, vc_1), (vc_4, vc_3, vc_1, vc_2), (vc_3, vc_4, vc_2, vc_1), (vc_3, vc_4, vc_1, vc_2).
Step 6: With all possible combinations of the vehicles in either descending or ascending destination order, this research checks which combination matches maximum with the current pattern of vehicles. To identify the maximum match, the number of movement operations required to convert the current pattern to the particular combination is calculated. A combination that requires a minimum number of movements is identified as the maximum match. If there is more than one combination that requires the minimum number of movements, the total distance the vehicles need to cover during the rearrangement process to transform from the current pattern to the combination is calculated. The combination with minimum travel distance is then considered as the maximum match.
Step 7: The vehicle combination with a maximum match with the current pattern is considered as the target order of the platoon. This pattern matching process minimizes the vehicles' movement to form an ordered platoon.
Step 8: The vehicles that are not as per the targeted order are adjusted to obtain the desired order.

Step 9: Similar to the greedy formation strategy, all the vehicles are moved to the same lane and their internal gaps are reduced by speed adjustment to form the platoon.

After their formation, the platoons move along the highway towards the destination ramps. Section 7.3 illustrates both formation strategies.

7.2.0.2 *Platoon Dissolution*

As the platoon moves through the highway, some of the platoon members approach their destination ramps. In the greedily formed platoons, they can be at any position in the platoon, and in the ordered platoons they are in consecutive positions at the head or tail, depending on whether the platoon has ascending or descending order. Those members leave the platoon and exit through the exit ramp. For the greedily formed platoons, the departure of some vehicles may result in a number of sub-platoons that will reduce their intermediate gaps and rebuild the platoon. Whereas, for the ordered platoons, departure of the vehicles do not disturb the rest of the platoon members. The exit of platoon members results in different scenarios as follows.

1. *Exit of platoon leader*: If the 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* (only in greedily formed platoons): 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 rebuild 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.

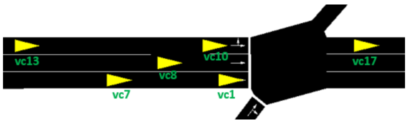
7.3 ILLUSTRATION OF THE IMPLEMENTATION

The formation and dissolution strategies are illustrated in this section.

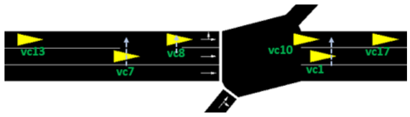
7.3.1 *Greedy Formation*

Figure 28 shows the steps of greedy formation 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 (Figure 28a). The leading vehicle



(a) Initial vehicles' sub-cluster



(b) Platoon members are getting their positions - lane change

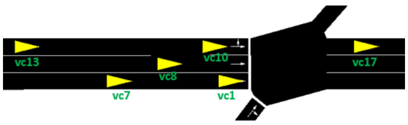
(c) Platoon formation - speed adjustment

Figure 28: Ad-hoc platoon formation by greedy strategy.

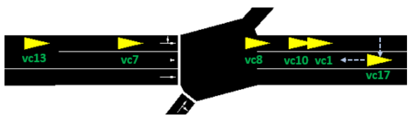
vc_{17} is selected as the platoon leader. The other five vehicles are considered as platoon followers. Platoon leader vc_{17} and two other vehicles vc_{10}, vc_{13} are already in left-most lane where the platoon will be formed. Therefore, those three vehicles do not change their lanes. The remaining three vehicles vc_1, vc_8, and vc_7 shift left in the following simulation steps to get positions in the platoon (Figure 28b). Once all vehicles are shifted to the left-most lane, the first vehicle pair (vc_1, vc_{17}) is identified. 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 Figure 28c. The complete platoon forms as ($vc_{13}, vc_7, vc_8, vc_{10}, vc_1, vc_{17}$), with vc_{17} as platoon leader and vc_{13} and last member.

7.3.2 *Ordered Formation*

The steps of the ordered platoon formation are shown in Figure 29.



(a) Initial vehicles' sub-cluster



(b) Platoon members rearrangement - speed adjustment

(c) Platoon members rearrangement – taking position

(d) Platoon formation - speed adjustment

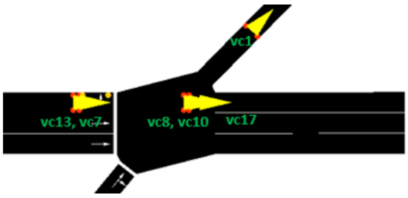
Figure 29: Ordered ad-hoc platoon formation.

Among the six vehicles, vc_1 and vc_7 have the nearest exit, through the ramp 28 km ahead from the starting point of the highway. vc_{13},

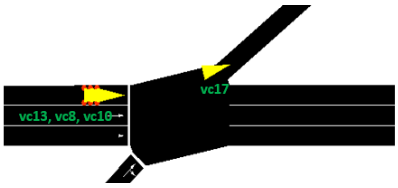
vc_{17} exit through the ramp 30 km ahead, and vc_8 exits through the ramp 34 km ahead. The farthest traveling vehicle is vc_{10} that exits through the ramp 38 km ahead. In total there are four unique destination ramps. Then all possible combinations of the vehicles are identified, first by exit ramps, then in both descending and ascending destination ramp order. In total there are eight different combinations. Among these eight combinations, the pattern P=(vc_7, vc_1, vc_{13}, vc_{17}, vc_8, vc_{10}) matches best with the initial pattern of the vehicles in the sub-cluster. P is selected as the target order of the platoon members. The vehicles not in this target order are now adjusting their speeds to obtain the target order (Figure 29b, Figure 29c). Once the target order is achieved, the intermediate gaps of the vehicles are reduced and consecutive merge operations are performed as described in the greedy formation to form the platoon. The complete platoon forms as (vc_7, vc_1, vc_{13}, vc_{17}, vc_8, vc_{10}), with vc_{10} as platoon leader and vc_7 and last member.

7.3.3 *Platoon Dissolution*

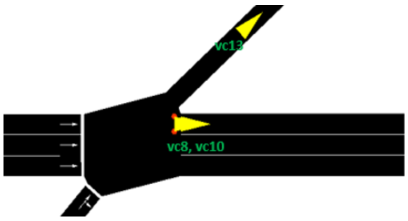
The platoon dissolution starts when one or more platoon members reach their exit ramp. Figure 30 shows a platoon dissolution process of greedy-based formation.



(a) Platoon follower leaves platoon



(b) Platoon leader leaves platoon



(c) Platoon tail member leaves platoon

Figure 30: Platoon dissolution.

In this example, two platoon followers vc_1 and vc_7 approach 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 (Figure 30a), the platoon leader vc_{17} turns into a 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 a free-flow vehicle. The members adjust their speeds and rebuild the platoon

($vc_{13}, vc_8, vc_{10}, vc_{17}$). At next exit ramp, platoon leader vc_{17} exits and vc_{10} becomes a new platoon leader (Figure 30b). The last member, vc_{13} also leaves through the same exit ramp (Figure 30c), which does not impact the rest of the platoon. At the next exit ramp vc_8 exits. Along with that, the platoon dissolution process completes. This is the death of the platoon.

7.4 EXPERIMENT

This section presents the experimental results of the ordered and greedy platoon formation strategy and their corresponding dissolution.

7.4.1 *Simulation Setup*

To simulate the platoons and the traffic, and to evaluate the fuel consumption in platooning and non-platooning scenarios, a 40 kilometer long straight three-lane highway is designed. The stretch consists of 20 segments of 2 km length each. In each segment, there is an entry ramp and an exit ramp. In a platoon's life-cycle, the vehicles follow the same speed dynamics as per the previous chapter. The vehicles can accelerate 1 m/s^2 and decelerate 4 m/s^2. The desirable speed of a free-flow vehicle or a platoon is 28 m/s, unless they are impeded by other leading vehicles. During the merge operations, the preceding vehicle or platoon reduces its speed up to 16 m/s. Then the preceding vehicle or platoon increases its speed again to obtain the predetermined intra-platoon headway and to form or enhance the platoon. During the platoon dissolution, if a member leaves from a middle position, the speed of the front part is adjusted to reduce the extra gap.

7.4.2 *Experimental Results*

This experiment considers 30 test cases where vehicles are initialized and randomly distributed in the simulation network with an average density of ten vehicles per km. Also, a flow of 360 vehicles per hour is initiated through the entry ramps to add some disturbances in the traffic. For each testcase, the simulation runs for three times.

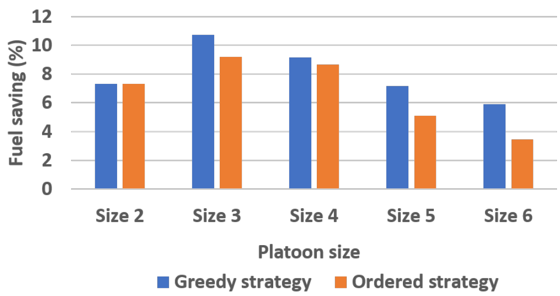
1. In the first simulation, the platoons are formed as per the greedy strategy. Once all vehicles are initialized, DBScan and SVM classification are applied to cluster and sub-cluster the vehicles. The platoons are formed from the sub-clusters. After traveling through the highway, the vehicles leave the platoon through exit ramps. Platoon rebuilding is performed if the platoon members leave the platoon from middle positions. The simulation runs

until the last platooning vehicle leaves the highway. The fuel consumption of all the vehicles is calculated that travel as a platoon.

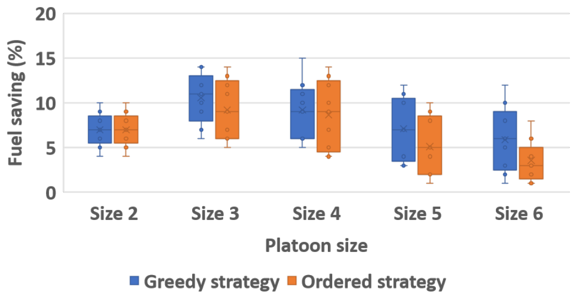
2. The second simulation performs ordered platoon formation. The vehicles are clustered and sub-clustered in a similar way. In this simulation, platoon rebuilding is not required. Here also the fuel consumption of platooning vehicles is computed.

3. In the third simulation, all vehicles are allowed to move freely as per IDM car-following model. Only the vehicles participating in platooning in the first two simulations are considered to compute the fuel consumption.

Finally, the percentage of fuel savings for greedy and ordered formations of the platoons are compared to the non-platooning scenario. Figure 31 shows the fuel-saving percentage and its variance for both formation strategies based on platoon size. Figure 32 shows the prediction accuracy for greedy and ordered formation and dissolution strategies with respect to the platoon size.



(a) Fuel saving based on platoon size



(b) Variance of fuel saving

Figure 31: Fuel saving percentages for greedy and ordered strategies.

7.5 DISCUSSION

From the experimental results the following points are observed:

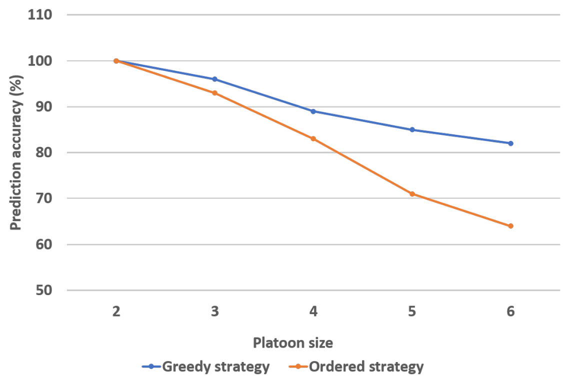


Figure 32: Prediction accuracy for greedy and ordered strategies.

- Figure 31 shows that for a platoon of size two the fuel saving is the same for greedy based platoon formation and ordered platoon formation. When the sub-cluster has only two vehicles, they are always ordered on their destinations, either farthest-to-nearest or nearest-to-farthest. Thus, there is neither a need for platoon rebuilding for the greedy strategy nor rearrangement of vehicles required in for the ordered strategy. For a platoon size of two, these two strategies become identical.

- When the platoon size exceeds two, the fuel-saving percentage for the greedy platoon formation strategy is higher than the ordered formation strategy. For the ordered formation, the vehicles have to be rearranged from their initial positions. For rearrangements, the vehicles travel for longer, increasing fuel consumption during platoon formation and decreasing the total platooning time. It appears that the additional costs at formation are higher. Comparatively, shorter distances involved in the greedy strategy's platoon rebuilding process. It makes the greedy strategy fuel-efficient.

- The percentage of fuel-saving is higher for platoon size three and platoon size four. For larger platoon size, the percentage falls for both strategies. As the size of platoon increases, there is more possibility of the randomness of the platoon members' destinations at the starting of formation. This incurs higher fuel consumption due to either the platoon rebuilding process in the greedy formation strategy or due to the vehicle rearrangement for the ordered formation strategy. Therefore, the average fuel-saving percentage decreases for larger platoons. Point to note, this research simulates the platoons on 40 km long highway. The larger platoons may become fuel-efficient for longer highways.

- This research used the SVM classification model to identify vehicles' clusters to form fuel-efficient platoons. Not all predictions result in fuel-efficient platoons. During the SVM classifier training, the research has used two vehicles in a simulation to identify if the platoon will be fuel-efficient or not based on three parameters. But for a platoon of size two, neither the platoon rebuilding nor the vehicle rearrangement processes are considered during training, which causes some inaccurate predictions at run time.

- For a platoon of size two, the additional fuel consumption is required only during platoon formation. There is no fuel expenditure for platoon rebuilding or vehicle rearrangement. In this case, the training and testing cases are identical, which gives 100% prediction accuracy. Therefore, the platooning always turns out fuel-efficient.

- Figure 31 shows the prediction accuracy in identifying fuel-efficient platoons falls for longer platoon sizes. For a platoon of size three, the prediction accuracy is 96% for greedy formation, and 93% for ordered formation, respectively. The percentage drops to 82% and 64% when the platoon size is six.

7.6 CONCLUSION

This chapter investigates a platoon's life-cycle in multi-lane highway where the formation and dissolution of platoons are performed on the fly. The platooning vehicles are selected through a clustering and classification process. Two ad-hoc formation strategies are modeled and implemented. In the first strategy, platoons are formed greedily from the sub-clustered vehicles, based on vehicles' positions, irrespective of their destinations. In the second strategy, platoons are formed in an ordered manner based on their destinations. A platoon dies as soon as the last two vehicles of a platoon split. The investigation focuses on the fuel efficiency of vehicles and compares platooning versus non-platooning scenarios.

The experimental results support the previous hypothesis that the ad-hoc vehicle platooning can be fuel-efficient compared to non-platooning. The fuel benefit depends on the parameters inter-vehicle distance, last platoonable point distance, and the speed difference. Based on the parameter values, the classification model identifies fuel-efficient vehicles to form platoons. The analysis supports the hypothesis that in multi-lane highway, the greedy approach of platoon formation is more beneficial compared to the ordered formation or a non-platooning scenario. Specially, when the platoon size is bigger, it is better to follow the greedy approach for the platoon formation. In general, a shorter platoon size and a higher travel distance of platoon guarantee fuel benefit.

8 DISCUSSION OF ACHIEVEMENTS

The discussion in this chapter has four main parts that match the four primary challenges of this research listed in Section 1.4. The first part is progress made by this research towards an agreement on platooning concepts, objects and operations, including a discussion to understand how the differing and incompatible definitions found in the literature review can be addressed. The second part talks about the possible improvement in the platoon formation by allowing flexible toolkit of platoon merge operations. The third part is about the achievement of a decision model that guides towards fuel-efficient platooning vehicles selection for ad-hoc platoon formation. The fourth part is a lesson towards a choice of ad-hoc platoon formation and dissolution strategies to ensure the platooning benefit.

8.1 ADDRESSING THE RESEARCH CHALLENGES

8.1.1 *The Progression of Conceptualization of Platooning Objects, Properties and Operations*

This section discusses the progress made towards conceptualization of vehicle platoon and platoon operations. It focuses on a categorization of the platooning objects and basic blocks of platoon operations and progresses to define the derived operations. The abstraction gained from this work is applied to understand and explain the differing definitions of platoon objects and operations from the literature.

The platooning projects and on-road trials referred in the literature mainly considered a planned way of platoon formation at source and dissolution at the destination. There is few literature (Dao, Huissoon, and Clark, 2013; Hall and Chin, 2005; Hobert, 2012) that proposed *ramp-based* and *ramp-highway-based* formations of platoons. In contrast, this research focuses on ad-hoc platoon formations and dissolution strategies where the free-flow vehicles form a platoon opportunistically, on the fly. To form a platoon in an ad-hoc manner, the very first requirement is to have a common language, i.e., a common understanding of *concepts* so that vehicles from different communities can talk and co-ordinate with each other. Chapter 3 began with the definitions of platoon objects and platoon operations in the literature and the purpose of defining them. Platoon objects were identified in the literature as of interest to numerous platoon projects and on-road platooning trials to support mainly the control strategies and vehicle-to-vehicle communication. The definitions are confined within a particular project or vehicles manufacturers. The definitions are specific to a project and solely related to the project's objective. There is no standard language yet. Also, the literature neither have any justification of the referred concepts nor have any categorization or abstraction of the concepts. Hence, this research defined basic blocks of platoon objects and platoon operations, namely, the atomic functions and primitive platoon operations which can be combined to represent any complex platoon behavior, namely, the derived platoon operation. To ensure the acceptability and coverage of the proposed conceptualization, each concept refereed in the literature is explained by the proposed conceptual model.

8.1.2 *The Progression of Modeling Flexible Platoon Merge Operations*

After defining the platoon objects and abstracting platoon operations in Chapter 5, this thesis focuses on the primitive platoon operations, more specifically, platoon merge operations. Research mainly considered the primitive platoon operation *tail merge* to perform the derived operation of platoon formation. Moreover, to evaluate platoon formation strategies a straight highway with intersections has been considered, that lacks the effect of feedback flow. With this setting, the vehicles move out from the network after some time and the full impact of merge operations cannot be captured. This thesis identified a requirement of the flexible merge operations in ad-hoc platoon formation. In ad-hoc formation a merging vehicle can express a merge request when approaching the platoon on the highway from the back, front or the side of the platoon. The research also finds that the effectiveness and success rate of merge operations are influenced by traffic. As per the proposed conceptual model, front and tail merge are the primitive operations and defined using basic functional blocks of atomic functions. Whereas, the middle merge falls under a higher level of abstraction in the derived operation category and comprises of one split and two tail merge operations. Hence, front and tail merge look attractive from an operational point of view. However, the research finding is that in dense traffic or during the lane merge middle merge may be cheaper or even the only option. Hence, the research focus shifts to modeling and implementation of the front merge, middle merge and tail merge operations and analyzing their impact. The impacts of the flexible merge operations are analyzed in the simulation environment with and without traffic. The research considered a circular network that compels the vehicles to move in a loop and the full impact of merge operations can be observed over any time frame. It establishes the efficiency of the middle merge operation in traffic in terms of merge time, merge success rate in ad-hoc platoon formation (Maiti et al., 2019b).

8.1.3 *The Progression towards Modeling Fuel-efficient Ad-hoc Platoon Formation and Dissolution*

This research found that when the vehicles travel as a platoon from source to destination, it is fuel-efficient compared to non-platooning. This is a well-established fact and reported in the literature. The question arises on the fuel efficiency of vehicle platoons when the platoons are formed in an ad-hoc manner, on the fly. This ad-hoc platoon formation comes with a risk of formation failure due to the surrounding traffic. Moreover, the fuel benefit from the formation is nullified if the members need to cover long distances for formation or if the platoon runs for a short time. This questions and the concept of ad-hoc platooning are rarely analyzed in the literature.

8.1.3.1 *Decision Model for Platooning Vehicle Selection*

Liang proposed a mathematical model to evaluate if it is fuel-efficient to catch up with a platoon for a heavy-duty vehicle (Liang, 2016). But the question remains how to select potential fuel-efficient vehicles from free-flow traffic and how to form platoons from those vehicles. Chapter 6 makes a progress to address the research challenge by *building a decision model that recommends a strategy of platooning vehicle selection to form fuel-efficient platoons*. The decision model is built based on DBScan clustering model and SVM classification model. Research demonstrates how to form fuel-efficient platoons based on this decision model. In this part of the research, the platoon formation is restricted in a single lane highway. Single lane restricts the vehicles to overtake and hence provides limited options of platoon formation. This restriction makes the decision model simple yet realistic. Later, this decision-making tool also used for multi-lane highway scenario.

8.1.3.2 *Platoon Formation and Dissolution Strategies*

A multi-lane highway enables the vehicles to change lane, overtake, and rearrange themselves. Therefore, the platoons can be formed in many different ways. Chapter 7 focuses on *modeling and implementation of ad-hoc platoon formation and dissolution strategies*. This research considered two different platoon formation and dissolution strategies namely, greedy formation and dissolution, and ordered formation and dissolution. In the greedy strategy, a member's current position is the decisive factor of the member's position in the formed platoon (Maiti et al., 2019a). This strategy incurs an additional fuel cost for platoon rebuild when a middle member leaves the platoon during platoon dissolution. In contrast, in the ordered strategy, a platoon member's destination decides the member's position and vehicles rearrangement is needed during the formation process. Hence, the research anticipates easy and quick formation for the greedy strategy and easy and quick dissolution for the ordered strategy. Here, the question remains which strategy will be more fuel-efficient. To answer this question, an effort is made to model and implement these two formation and dissolution strategies in the simulation environment. The experimental results have shown that the greedy approach of platoon formation and dissolution is more beneficial for ad-hoc platoon formation under the test scenario. It also reveals the fact that rearrangement of the vehicles during a platoon formation is costlier in terms of fuel expenditure compared to rebuild of a platoon during platoon dissolution.

8.2 EVALUATION OF HYPOTHESES

This research goal is to study the behavior of vehicle platoons and platoon formation and dissolution strategies. Research mainly focuses on ad-hoc platoon formation and dissolution and guides toward fuel-efficient platoon formation. To fulfill the research goal four different research challenges are identified. Each research challenge associates with a hypothesis and a number of sub-challenges. The research work has progressively worked to prove these hypotheses. Based on the illustrations and evaluations in Chapter 3, Chapter 5, Chapter 6, and Chapter 7 this section evaluates all the hypotheses.

8.2.1 *Hypothesis 1*

Any behavior of platoons refereed in the existing research literature can be represented as a combination of basic blocks of platoon operations.

Chapter 3 has proposed an ontology-based conceptual model of platoon object, properties and operations in order to standardize them for ad-hoc platooning. This research section developed a small set of atomic functions and primitive operations. The claim, or the hypothesis, of this part of the research is that any behavior of platoons presented in the existing research literature can be represented as a derived operation. Since proof of this claim is impossible by deduction, the research starts an inductive proof. The research illustrates two derived operations, namely, *middle merge* and *change leader* to show how the primitive operations can be aggregated to define these two platoon operations. Other than these two derived operations a complex behavior of platoon that is a formation of platoon followed my a middle merge are also analyzed to support this claim. The claim can be upheld as long as no other complex behavior can be found that cannot be represented by combining these atomic functions and primitive operations. A related claim is that the set of atomic functions is minimal: none of them can be given up (they are all used at some stage in the primitive and derived operations), and none of them can be replaced by one of the other functions, or a combination thereof.

An effort towards the proof by induction is made by going back to the different platooning projects discussed in the literature review. Their objects, properties, and operations are represented by the elements of the ontology presented in this research. Table 1 and 2 shows the mapping of the various platooning *objects* and *operations* in Section 3.4 to the proposed concepts to prove the hypothesis.

8.2.2 *Hypothesis 2*

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.

In order to evaluate Hypothesis 2, Chapter 5 focuses on implementation of three merge operations in a simulation environment with and without traffic. Figure 19 shows the variation of merging time of front, middle and tail merge based on the distance of the initial position of the vehicle in the absence of traffic. The graph pattern supports research assumption 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 experimental results of the three merge operations that consider traffic are presented in Table 6, Table 7. Figure 21 provides a comparison of three merge operations in terms of merge completion time, platoon travel distance, average traffic speed and merge success rate. It reveals the fact 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. This implies traffic has more impact on the front and tail merge whereas middle merge is comparatively less affected. On the contrary, the middle merge has a higher impact on traffic as it 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 merge completion time or travel distance, or to maximize merge success rate or average traffic speed. This provides evidence to prove Hypothesis 2.

8.2.3 *Hypothesis 3*

A guided way of ad-hoc platoon formation preserves platooning benefits compared to the free-flow traffic.

After conceptualizing platoon objects, properties and operations in Chapter 3 and analyzing primitive operation merge in Chapter 5, Chapter 6 focuses on ad-hoc formation of platoons. In this part of the research, a SVM based decision model is built to identify potential fuel-efficient vehicles for platooning. Three parameters inter-vehicle distance, last platooonable point distance, and the speed difference of vehicles are used to train the decision model thus plays a guiding factor for fuel-efficient platoon generation. Further, the research demonstrated a real-time use of the decision model to select vehicles from traffic that guides to form fuel-efficient platoons. The experimental results show the accuracy of the decision model. The accuracy of forming fuel-efficient platoons proves Hypothesis 3 that a guided way of ad-hoc platoon formation preserves the platooning benefit compared to the free-flow traffic.

8.2.4 *Hypothesis 4*

Greedy ad-hoc platoon formation-dissolution strategy outperforms ordered ad-hoc formation dissolution strategy in multi-lane highway.

The last phase of the research presented in Chapter 7 models platoon's life-cycle from birth to death focuses on the comparative study of platoon formation and dissolution strategies. Two ad-hoc formation strategies are implemented in the simulation platform with multi-lane highway. In the first strategy, platoons are formed greedily from the sub-clustered vehicles, based on vehicles' positions, irrespective of their destinations. In the second strategy, platoons are formed in an ordered manner based on their destinations. The comparison considers fuel efficiency of vehicles during platooning for two strategies versus non-platooning scenario. The analysis supports hypothesis 4 and shows the greedy approach of platoon formation is more beneficial compared to the ordered formation or a non-platooning scenario. Specially, when the platoon size is bigger, it is better to follow the greedy approach for the platoon formation. A shorter platoon size and a higher travel distance of platoon ensure fuel benefit from ad-hoc platooning.

Based on the evaluation of the four hypotheses this research fulfills the research goal of studying the behavior of vehicle platoons specially for ad-hoc platoon formation and dissolution, thus to provide guidance for fuel-efficient platooning.

8.3 LIMITATIONS

Despite the efficacy of the models developed in this research (Chapter 3, Chapter 5, Chapter 6, and Chapter 7) there are some limitations as follows.

- Conceptualization model - The ontological model is developed in this research to standardize platoon concepts to enable ad-hoc platooning across different platoon communities. To ensure the completeness of the proposed model, this research revisited the literature and mapped all platoon objects and platoon operations referred in the literature using the proposed concept.

The research claimed all complex platoon behavior can be expressed with the minimal set of proposed atomic functions and primitive operations. This proof is limited by proof of induction and valid till as long as no complex behavior can be found that cannot be represented by combining these atomic functions and primitive operations. The research proposed a way of standardization of concepts for ad-hoc platooning. The platooning communities yet to accept this standardization and enhance this conceptualization as per their requirement.

- Simulation constraints - The implementation part of this research - the simulation environment is restricted in different ways. An important aspect of vehicle platooning is communication and co-ordination. As this research mainly investigated the operational aspects, the communication details and communication related effects, such as communication delay or disturbances, are neglected in the simulation. However, the coordination of platoon members is done through the external controller MATLAB.

  This research evaluated platoon operations using different metrics such as merge completion time, merge completion distance, average traffic speed during merge operations and merge success rate. However, the safety aspects during the operations are not explored. Research shows middle merge operation outperforms other merge operation on an average in presence of traffic. But, the question remains, whether it is safe to perform middle merge operation in a traffic.

  Throughout the implementation, this research performed single platoon operation at a time. However, one can think of platoon performing operations executed in parallel. For example, parallel merge operations during the platoon formation may reduce formation time and can increase fuel efficiency from platooning. However, consideration of parallel operations increases complexity in coordination and requires proper planning for their order of execution.

- Environmental constraints – In this research a vehicle decides to form platoon or to travel alone based on the fuel consumption of the vehicle. A vehicle's fuel consumption depends on the environment factors, such as road condition, or the gradient of the road. The simulation considers ideal road conditions, no gradient of the road, and also ignores other environmental factors.

9 CONCLUSION

This chapter first revisits the research gaps and the objectives motivating this research. Then, following a review of results and findings. This thesis is evaluated with respect to the research challenges. The major contributions are presented, and the chapter is completed by a discussion of future works.

9.1 RESEARCH GAPS AND OBJECTIVES

The aim of this research was to study on the behavior of vehicle platoons and platoon formation and dissolution strategies. The ultimate research motivation was to form platoons in an ad-hoc manner and to analyze platooning benefits that can be achieved from the ad-hoc formation. To achieve this aim, at first this research defined platooning objects and conceptualize platoon operations so that the vehicles from different communities can interact co-operate with each other for formation and dissolution. The next level of research is motivated by the requirement of flexible merge operations which is the building block of derived operation of platoon formation. To achieve this goal, three different merge operations are analyzed in a traffic scenario. The objective is to understand their importance in platoon formation and their impact on traffic. In the final motivation of the research is to model and investigate ad-hoc platoon formation and dissolution strategies. To achieve this a decision model is proposed that makes selection of potential vehicles from traffic to form fuel efficient platoons. In this part, the proposed framework demonstrates the process of vehicle selection, platoon formation and dissolution in a simulation environment for a single and multi-lane highway. Two types of formation and dissolution strategies are implemented based on the proposed framework. The comparison of two strategies provides insights that help to select formation strategy in given traffic scenario.

9.2 MAJOR RESULTS AND FINDINGS

This research has adopted a progressive bottom-up approach, firstly exploring whether the existing concepts of platoon and platoon operations are adaptable for ad-hoc platoon formation and progressed to explore a range of concepts defined in the literature and their purpose. The survey reveals the concepts varies in different platooning communities and lack of standardization whereas the ad-hoc platoon formation demands a common acceptance of concepts. To address the issue this research proposed an ontological model of platooning objects and properties and abstract basic building blocks of platoon operations that covers the concepts referred to the literature and suitable for ad-hoc platooning. The research further proceeded for the application of flexible merge operations required for ad-hoc platoon formation. Finally, the ad-hoc platooning strategies are modeled and implemented. The results and major findings are detailed in following sections reflecting the initial research focus on conceptual modeling, and followed by the practical implementation of platoon operations in the simulation environment.

9.2.1 *Research Focus on Conceptual Modeling of Platoon Objects, Properties and Platoon Operations*

Chapter 3 focused on conceptualization of platoon objects, properties and platoon operations to standardize them and build the fundamental ground to support ad-hoc platoon formation and dissolution. A summary of major results and findings related to this part of research includes:

- *Definition of platoon objects and platoon properties*
- *Identification and abstraction of platoon operations*
- *A demonstration of how objects, properties, and operations interact to enable any complex behavior*

The first significant finding in Chapter 3 is a minimal set of platoon objects - a platoon class and a vehicle class, where every vehicle is either platoon leader (potentially with no followers) or platoon follower. Most of the platoon communities used three types of platoon objects: platoon leader, platoon follower, and platoon, and sometimes an additional concept of a free vehicle. Exceptionally, the SARTRE project defined eight types of platoon objects, namely lead vehicle, following vehicle, other vehicle, potential following vehicle, potential lead vehicle, potential platoon vehicle, or platoon vehicle. This research revealed that only two platoon objects platoon leader and platoon follower are sufficient to address all platoon objects referred to the literature. To prove the claim, the platoon objects referred to the literature are revisited and each object is represented using the proposed two objects along with a logical explanation of the representation. The vehicles without platooning capability are not considered in the proposed conceptualization as they cannot be part of a platoon. However, a single free-flow vehicle is considered as a degenerated platoon or a platoon leader without any follower. Platooning projects referred some of the platoon properties for platoon control perspective. The proposed conceptualization abstracted platoon properties in two different levels. The lower level defines properties of individual platoon members whereas the higher level defines properties of a platoon as a whole. A platoon leader's decisions and the corresponding platoon operations depend on both higher and lower level property values. The properties considered in this research are the mandatory ones for specifying the operations of a vehicle in a platooning context. However, the properties can be extended based on the requirements of individual implementation.

Further research findings lead towards abstraction of platoon operations. From the survey and analysis, this research developed a small set of atomic functions that are further combined to produce two primitive operations, merge, and split. These atomic functions are the basic blocks of platoon operations. The analysis revealed that any platoon behavior can be represented as combinations of atomic functions and primitive platoon operations. To support this insight the complex platoon behavior such as middle merge, change leader and give a way are explained. To establish the finding, this research further revisited the projects and explained all operations referred in the literature with the help of basic operation blocks. Finally, a series of platoon operations are demonstrated to show how the defined objects, properties, and operations interact with each other that represents a platoon's behavior.

9.2.2 *Research Focus on the Importance of Flexible Merge Operations and the Operations' Impact on the Traffic*

Building on the foundation developed in previous chapters, Chapter 5 shifted the focus from conceptual model being to implementation of the platoon operations. It commences by introducing front and middle merge operations that can provide potential benefit in ad-hoc platoon formation. Chapter 5 models and implements merge operations and focuses on a summary of results and findings includes:

- *Impact of the merge operations on traffic and traffic's impact on the merge operations*
- *Experimental results indicating the potential to use flexible merge operations during platoon formation*

A major finding of Chapter 5 is the potentials of different merge operations to increase platooning benefits under various traffic scenario. The experimental results support the fact that in the absence of traffic, the vehicle merge time is proportional to the distance of the vehicle and for the same distance, the merge time of middle merge is higher than tail merge or front merge. The results also reveal that under traffic scenario, the middle merge is more preferable compared to front and tail merge in terms of merge completion time, platoon travel distance, and merge success rate. The analysis found that while selecting the preferred mergeable vehicle, there are multiple options for merge positions for middle merge, 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. The longer distance of merging vehicle increases merge completion time and platoon travel distance in traffic. With the increase of traffic density, middle merge achieves higher merge success rate on average compared to the other two merge operations. But on the flip side, the middle merge impedes the average traffic speed more compared to the front and tail merge operations. Thus, the main finding from this section is that the use of flexible merge operations can increase the platoon benefit. The selection of merge operations should be based on the objective such as minimum merge time or minimum impact on traffic flow.

9.2.3 *Research Focus on Potential Vehicle Selection and Ad-hoc Platoon Formation and Dissolution*

Chapter 6 begins with a finding that in ad-hoc platooning, only some formations could be fuel efficient out of all possible opportunities of platoon formation. More specifically, wheather a platoon of two vehicles will be fuel efficient or not depends on the three parameters: the inter-vehicle distance, the distance to the last platoonable point, and the speed difference of those two merging vehicles. Therefore, selection of platooning vehicles and the formation strategy is important for ad-hoc formation. Chapter 6 focused on a framework of platooning vehicle selection and fuel-efficient platoon formation. The summary of results and findings includes:

- *A selection of platoonable vehicles from the traffic that provides potential fuel benefit*
- *A decision model of fuel efficiency based on the inter-vehicle distance, the distance to the last platoonable point, and the speed difference of vehicles*
- *A demonstration and validation of real-time use of the decision model to generate and maintain platoons in a fuel-efficient way*

Chapter 7 deals with a complex scenario of platoon formation and dissolution by considering multi-lane highway. Multi-lane highway enables the facility of lane change, overtake and rearrangement of vehicles. Hence, platoon can be formed in many different ways. This research focused on the implementation of two different platoon formation and dissolution strategies based on the proposed framework. Among the two strategies, one strategy only considers a vehicle's current position during platoon formation and the other strategy considers a vehicle's destinations for platoon formation. The summary of results and findings includes:

- *Modeling and implementing the greedy and the ordered platoon formation and dissolution strategies on a multi-lane highway*
- *An analysis of the fuel efficiency of the proposed formation and dissolution strategies*
- *A guideline for the choice of a formation strategy in a given traffic situation*

The results indicate that the greedy approach of platoon formation is more beneficial compared to the ordered formation or a non-platooning scenario. Interesting findings included that a shorter platoon size and a higher travel distance of platoon ensures fuel benefit from ad-hoc platooning. When the platoon size is bigger, it is better to follow the greedy approach for the platoon formation.

9.3 RESEARCH CONTRIBUTIONS

This research contributes broadly to platoon behavior focused on ad-hoc platoon formation and dissolution. Major contributions include:

- A comprehensive analysis of platoon concepts used in different platoon projects is provided in the literature review. Further, this research defines platoon ontology that conceptualize the platooning objects and platoon properties, and platoon operations in order to standardize them. The research demonstrates how objects, properties, and operations interact to enable any complex behavior of platoon.
- This research models and implements different platoon merge operations and scenarios in a simulation platform. This research analyzes the merge 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.
- A clustering and classification based platooning vehicle selection model is proposed. This research demonstrates and validates a real-time decision model that guides to generate and maintain platoons in a fuel-efficient way.
- Finally, this research analyzes the fuel efficiency of two ad-hoc platoon formation and dissolution strategies on a multi-lane highway. This part of research contributes towards identifying fuel-efficient platoon formation and dissolution strategy in a given traffic situation.

9.4 FUTURE WORK

This research could be extended in various direction. The primary direction recommended for future work is to evaluate the ad-hoc platooning in terms of travel time and average traffic speed which is not covered in this research. This research considered the vehicles to slow down to form platoons in an ad-hoc manner and then speed up to travel in a desired speed of platoon. This process impacts on vehicle's travel time that needs an investigation.

In this research, SVM classification is used as a decision model to identify potential vehicles to form platoons. While training the SVM model, three features, namely the inter-vehicle distance, the distance to the last platoonable point, and the speed difference are considered as the feature set. Consideration of traffic during the training might increase the prediction accuracy in the validation phase, that could be a future research direction. Also, as an alternative to SVM, other learning models can be used to see if the prediction accuracy improves with other models. A comprehensive sensitivity analysis that considers all parameters of the car-following model and the fuel consumption model is beyond the scope of this thesis.

Future research can consider environmental constraints, such as road condition, road gradient and can adopt a real road network to simulate platoons. Currently, while generating a platoon, the merge operations are executed one after the other. A parallel merge operation would lead to even more fuel efficiency in platoon formation. However, it is challenging to decide the merge order and a number of merge operations at a time. Future work can address this challenge.

From an ontology perspective, an addition of a reasoning module with the platoon ontology will support the advance decision-making process. By considering Vehicle to Infrastructure (V2I) communication or communication with traffic signals, a platoon can reason and make a decision a priori. For example, if a bridge with a specific weight limit is ahead, the platoon leader can decide how to split the platoon and when.

From an application perspective, vehicle platoons can be extended in public transport and inner city traffic to reduce road capacity and to reduce the travel time. Incorporation of planners can help to plan a trip for the platoon.

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DECLARATION

I declare that this thesis has been composed solely by myself Santa Maiti. Some chapters are revised based on published or submitted manuscripts of which I am the first author and my contributions have been explained individually. Except where states by reference or acknowledgment, the thesis is entirely of my own. The thesis in whole has not been submitted in any previous application for a degree.

Melbourne, Australia, April 2020

Santa Maiti