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Investigating Strategies for Building Platoons of Cars

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Investigating Strategies for Building Platoons of Cars

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(Julian Heinovski)
Paderborn, 17. September 2018

Abstract

We study the problem of platoon formation, trying to optimize traveling time and fuel consumption based on-car-to platoon assignments. The general concept of platooning, i.e., cars traveling in form of a road train with minimized safety gaps, has been studied in depth and we see first field trials on the road. A number of projects already convinced the public that platooning helps substantially reducing fuel consumption, along with emissions, and offers better road utilization. Currently, most research focuses on improved reliability of the necessary communication protocols to achieve perfect string stability with guaranteed safety measures. One aspect, however, remained unexplored: the problem of assigning cars to platoons. Based on the capabilities of individual cars (e.g., max. acceleration or speed) and preferences of the driver (e.g., min/max. traveling speed, preference on travel time vs. fuel consumption), the assignment decision will be different. We formulate an optimization problem and develop a set of protocols (centralized and distributed) to support platoon formation. In an extensive series of simulation experiments, we show that our protocols not just help forming platoons, but also take care of the individual requirements of cars and drivers. The selection of the formation approach as well as the willingness to compromise influences the platoon assignments. Considering the selected metrics, a better overall performance can be achieved using the distributed approach, e.g., longer platoons can be formed and more fuel can be saved.

Kurzfassung

Wir untersuchen das Problem der Formierung von Platoons und versuchen, Reisezeit und Kraftstoffverbrauch von Fahrzeugen durch geeignete Platoon-Zuordnungen zu optimieren. Das generelle-Platooning Konzept, bei dem Fahrzeuge mit sehr geringem Sicherheitsabständen hintereinander fahren und sogenannte Road-Trains formen, wurde bereits im Detail untersucht, unter anderem in realen Testläufen mit echten Kraftfahrzeugen. Pilotprojekte haben gezeigt, dass Platooning sowohl signifikant den Kraftstoffverbrauch senken als auch die Ausnutzung der Kapazität von Straßen steigern kann. Während sich aktuelle Studien weitgehend damit beschäftigen, die Verlässlichkeit der benötigten Kommunikationsprotokolle zu verbessern, um konstante Abstände einzuhalten und ein sicheres Verhalten zu erreichen, wird ein wichtiger Aspekt vernachlässigt: Das Problem der Zuordnung von Kraftfahrzeugen zu Platoons. Diese Zuordnung allerdings stark von den Möglichkeiten einzelner Fahrzeuge (zum Beispiel maximale Beschleunigung oder Geschwindigkeit) und den Präferenzen des Fahrers (zum Beispiel gewünschte Reisegeschwindigkeit und dem Kompromiss zwischen Reisedauer und Kraftstoffverbrauch) ab. Um das Problem der Zuordnung zu untersuchen, formulieren wir ein Optimierungsproblem und entwickeln zwei Lösungsansätze, einen zentralisierten und einen verteilten. Mit Hilfe einer umfangreichen Simulationsstudie zeigen wir, dass unsere Ansätze nicht nur Platoons formen, sondern auch die individuellen Anforderungen der Fahrzeuge und Fahrer berücksichtigen. Dabei hat sowohl die Wahl des Ansatzes als auch die Bereitschaft zur Abweichung von individuellen Präfenzen einen großen Einfluss auf die Platoon-Zuordnungen. Anhand der ausgewählten Metriken führt der verteilte Ansatz zu einem besseren Ergebnis, zum Beispiel zu längeren Platoons und größeren Einsparungen beim Kraftstoffverbrauch.

Contents

Chapter 1

Introduction

ROAD traffic has been growing constantly during the last years. For example, passenger transport increased by 8 % from 2005 to 2015 in Europe and the individual car is still the major transportation system with a share of more than 71 % of Europe (2015) [1], and more than 80 % in Germany (2015) [2], in comparison to public transport. Additionally, the overall traveled distance increased as well as the number of privately owned cars. In Germany, the latter grew by 1.6 % to 45.8 million from 2017 to 2018 [2]. Having this many vehicles on the road leads to issues like environmental pollution (due to increased emissions) and congestion on the roads.

In order to cope with the continuously growing traffic needs, the concept of *platooning* has been developed [3, 4]. In platooning, multiple vehicles form a *road-train* and drive with a very small safety gap between each other to increase the road utilization. This small gap can be maintained by driving autonomously using Cooperative Adaptive Cruise Control (CACC), which combines data from local sensors (e.g., the distance to the previous vehicle measured by radar) and information from other vehicles via Inter-Vehicle Communication (IVC) [5]. Besides a better utilization of the road, platooning also brings other benefits such as a reduced air drag, thus, reducing the fuel consumption [6]. Furthermore, smoother speed changes by the autonomous driving system lead to improved traffic flows and increase the driving comfort [7].

The concept of platooning has been investigated in depth in the literature and in field trials on the road. Well known projects in the field are PATH [3, 8] and SARTRE [9, 10], both of which demonstrated the technical feasibility of stable platooning on the road – certainly limited to a few cars. Ongoing research mainly focuses on maintaining existing platoons, improving reliability of the necessary IVC protocols in order to achieve perfect string stability with guaranteed safety measures [11–13]. Many studies either consider pre-configured platoons or just do ad-hoc formation, i.e., a vehicle is joining the closest one in front using Adaptive Cruise Control (ACC). Therefore, platoon formation has either been artificial or only very basic, thus, not being very realistic or useful in terms of cost and benefit.

However, the typical situation on a freeway will be different. Individual cars are entering a freeway and drive on their own until they find an appropriate platoon (or another individual car) to team up with in a platoon. Therefore, solving the challenge of *platoon formation* or, more specifically, selecting candidate vehicles, is the next important step towards platooning. Once candidate vehicles are selected by some formation strategy, the cars should perform maneuvers to join an existing or form a new platoon [14, 15].

For platoon formation, a car has to start searching for candidates either immediately when entering the freeway, or at a later point in time. If there is a platoon, the car may become part of it and the search is over; otherwise, a new platoon has to be formed. In any case, a dynamic formation process is necessary, consisting of finding candidate platoons/vehicles and then joining/forming the platoon via a join maneuver.

In this thesis, we first study this problem analytically before presenting both a centralized and a distributed approach for platoon formation. The centralized approach uses global knowledge about all cars in the scenario to make assignment decisions, while running on a central entity in the network. In the distributed approach, the algorithm is running on every car in the scenario, therefore, having only limited local knowledge about other cars. We compare both approaches for the same strategy to study their respective advantages and weaknesses in an extensive set of simulation experiments.

Our main contributions can be summarized as follows:

- We provide an in-depth study of platoon formation challenges and analytically explore the problem,
- we develop both a centralized and a distributed strategy and the respective communication protocols, and
- we perform an extensive performance evaluation of both strategies and discuss the results, showing that the selection of the approach as well as the willingness to compromise has an impact on the resulting formations and benefits.

Based on this thesis, we have submitted a conference paper for publication at IEEE Vehicular Networking Conference (VNC) 2018, which is not yet published, as it is still in peer-review:

Julian Heinovski and Falko Dressler, "**Platoon Formation: Optimized Car to Platoon Assignment Strategies and Protocols,**" 10th IEEE Vehicular Networking Conference (VNC 2018), Taipei, Taiwan, December, 2018. (in peer-review)

Chapter 2

Fundamentals & Background

THIS chapter gives an overview of trends in the automotive industry regarding automation in Section 2.1 and connected vehicles in Section 2.2. It describes the combination of both aforementioned trends in Section 2.3 and explains vehicle platooning as major application use case in Section 2.4. Furthermore, it describes tools to study Vehicular Ad Hoc Networks (VANETs) and especially cooperative mobile systems such as platoons in Section 2.5.

2.1 Advanced Driver Assistance Systems

A major trend in driving today is assisted driving where data from multiple sensors in the car is fed to and evaluated by a built-in computer. This computer is programmed to assist the driver in a variety of tasks, aiming at improving the driver's safety and convenience. To do so, all relevant sensors are constantly monitoring the car's status and its environment to be able to immediately to react to changes. The spectrum of these so-called Advanced Driver Assistance Systems (ADASs) last from collision prevention over braking assistance via driver state monitoring up to lane assistance[1].

With even more of those ADASs included, the human driver has to accomplish less work, as more and more behavior of the car can be controlled by a computer. Even driving itself can already partly be automated, especially when driving on a highway. Multiple stages of such automation systems are described by Raza and Ioannou [16] as Advanced Highway Systems (AHSs). In this context, control of the speed of a vehicle is called *longitudinal control*, whereas control of the lane a vehicle is driving on is called *lateral control*.

[1]A comprehensive overview of assistance systems can be found at `https://mycardoeswhat.org/safety-features/`.

2.1.1 Cruise Control

The first stage of automation is Cruise Control (CC), where the driver of a vehicle selects a desired speed and the control system maintains this speed by automatically accelerating the vehicle. Also the behavior of accelerating back to the desired speed after manual deceleration can be configured. Therefore, this control system can improve the convenience for the driver when driving the same speed for a long time, especially on highways and freeways.

A scenario with two CC enabled vehicles is depicted in Figure 2.1. The vehicles drive individually with large safety gaps while the driving speed is maintained by the CC. As long as all vehicles drive the same speed, they can follow each other without any safety issues. However, if one of them breaks, the (human) driver has to decelerate or brake manually, since CC cannot automate this. Also, the driver has to maintain lateral control.

CC uses a Proportional Integral (PI) controller in order to achieve the desired speed and not overestimate the employed acceleration [17]. According to Rajamani [18], the desired acceleration u for the vehicle is based on the current speed $\dot{x}$ and the desired speed $\dot{x}_d$ and can be calculated by

$$u = -k_p(\dot{x} - \dot{x}_d) - k_i \int \dot{x} - \dot{x}_d \, dt \ , \tag{2.1}$$

where k_p and k_i are tuning parameters for the system.

2.1.2 Adaptive Cruise Control

The next stage of automation defined by Raza and Ioannou [16] is Adaptive Cruise Control (ACC). Here, the driver again selects a desired speed and, additionally, a headway time to vehicles in front. The control system then maintains the desired speed by controlling acceleration and deceleration of the vehicle. Additionally, if there is another vehicle in front, it keeps a constant gap configured by the headway time. Again, the (human) driver has to maintain lateral control. However, in contrary to CC, the control system automatically decelerates if the distance to the front vehicles falls below the safety gap defined by the headway time.

Figure 2.1 – Two vehicles are driving individually with a large safety gap while the driving speed is maintained by Cruise Control.

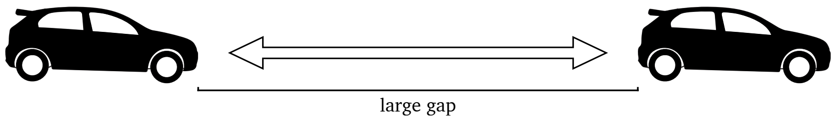

Figure 2.2 – Two vehicles are driving individually with a large safety gap while being partly automated by Adaptive Cruise Control. The arrow depicts the measurements of relative distance and speed using RADAR or LIDAR.

Similar to the scenario shown in Figure 2.1, Figure 2.2 depicts two vehicles, this time however, being controlled by ACC. As indicated by the arrows between vehicles, this control system measures the distance and the relative speed to the preceding vehicle by a RADAR or LIDAR sensor. Using these distance and speed measurements, according to Rajamani [18], the desired acceleration u to be implemented by the system then can be calculated by

$$u_i = -\frac{1}{T}\left(\dot{x}_i - \dot{x}_{i-1} + \lambda\left(x_i - x_{i-1} + l_{i-1} + T\dot{x}_i\right)\right) \;, \tag{2.2}$$

where $\dot{x}_i$ and $\dot{x}_{i-1}$ are the speeds of vehicles i and $i-1$, x_i and x_{i-1} are their positions, $(\dot{x}_i - \dot{x}_{i-1})$ is the relative speed, $(x_i - x_{i-1} + l_{i-1})$ is the relative distance, l_{i-1} is the length of the front vehicle, λ is a tuning parameter and T is the selected headway time.

The distance $T \cdot \dot{x}_i$ is not fixed but depends on the cruising speed of both vehicles. Since it is constant in time T, it increases as the cruising speed of the vehicle increases. This is called a constant time-gap policy.

The reactivity of the system depends on the actuation lag of the engine and the sampling rate of the sensor. In order to achieve tight following of cars, the headway time has to be twice the actuation lag [18]. Otherwise, spacing errors, changes in speed or acceleration are amplified toward the end of a sequence of following cars, thus, leading to an unstable and unsafe system. A typical value for the actuation lag is 0.5, thus, a minimum value for T is 1 s, which leads already to a rather large spacing when driving at typical freeway speeds. Therefore, ACC is not feasible for tight following of cars.

2.2 Intelligent Transportation Systems

Another big trend in today's automotive industry are Intelligent Transportation Systems (ITSs). Cars are equipped with wireless networking technology and they are connected to the Internet. The popularity of these connectivity features has been growing in recent years. A variety of models from different car manufacturers can already be connected to the Internet via cellular technologies such as Long-Term Evolution (LTE).

Additional to connecting cars to the Internet, the idea of connecting cars to each other and to other entities in the environment, e.g., Intelligent Traffic Lights (ITLs) via Inter-Vehicle Communication (IVC), has been researched for some time now. Due to the necessity of infrastructure such as Roadside Units (RSUs) and backbone networks for cellular technologies, Distributed Short-Range Communication (DSRC) (i.e., vehicular ad-hoc communication) has been standardized in IEEE 802.11p [19]. It is an amendment to the IEEE 802.11 WLAN standard [20] and was designed to support the different characteristics of IVC and Roadside-to-Vehicle Communication (RVC) in comparison to usual wireless communications [21]. The standard extends the Orthogonal Frequency Division Multiplexing (OFDM) physical layer (from IEEE 802.11a [22]) to operate in the 5.9 GHz band. Additionally, it also introduces a new operation mode, called Outside the Context of a BSS (OCB) mode, which allows nodes to operate without being part of a Basic Service Set (BSS). Instead of a lengthy join procedure to establish parameters like modulation and coding scheme, the node uses well-known parameters for accessing the channel [21]. For channel access, however, the standard still uses Carrier Sensing Multiple Access (CSMA) with Collision Avoidance (CSMA/CA), inherited from standard IEEE 802.11 WLAN.

Building upon IEEE 802.11p, the IEEE 1609 WAVE family of standards was designed to represent a complete ITS stack in the U.S. [23]. It adds switching between multiple wireless channels, security and QoS functionality. Also building on IEEE 802.11p, the ETSI ITS-G5 family of standards [24] was developed for IVC and RVC in Europe. In comparison to IEEE 1609.4, this standards uses less channels, a slightly different frequency and no channel switching.

Parallel to the developments in the U.S. and Europe, the Japanese research and standardization organization for radio telecommunication and broadcasting (ARIB) has developed ARIB STD-T109 [25], a standard for operating ITS in the 700 MHz band. In order to cope with a more congested channel due to a bigger transmission range of the lower frequency, the standard implements a Time Division Multiple Access (TDMA) scheme for channel access, thus, giving priority to RSUs transmissions [26].

So far, DSRC (or a combination of different technologies called heterogeneous networking) is mostly used for IVC and ITS applications. However, due to the lack of unused Radio Frequency (RF) spectrum, other communication technologies for the use in ITS are being researched, one of which is Visible Light Communication (VLC). In VLC, the signal, which is emitted by a LED and received by a photo diode, is not transmitted via RF bands but in the visible part of the electromagnetic spectrum [27]. This has multiple advantages such as a large and also unregulated frequency spectrum and full duplex operation (due to the transmitter and the receiver being two different devices). *"LED-based light modules are becoming increasingly* *popular in the automotive industry"* [27], since a usable VLC emitter is already in place, thus, VLC seems to be promising for the vehicular domain in particular.

Independent from the technology, there is a continuously growing interest in ITS and IVC. In fact, first deployments of vehicular networking around the world are already happening: Car manufacturers in Japan (e.g. Toyota) are selling first car models that include ITS functionality [26], plans to make ITS mandatory were announced by the U.S. government [28], and Volkswagen announced adding DSRC technology, called *pWLAN*, to all new cars starting from 2019 [29].

2.3 Cooperative Driving

A very recent trend in the automotive industry, called *cooperative driving*, combines ADASs with IVC to utilize the wireless technology as another sensor providing data about the environment to the control system. Now, not only the current state of the environment can be observed but also intended changes, such as acceleration or turn maneuvers of cars. Advanced Driver Assistance Systems can utilize this information to make better decisions about their behavior.

A variety of different use cases has been proposed. In Intersection Collision-Avoidance (ICA), vehicles can inform other vehicles and traffic participants about their intention, using Cooperative Awareness Messages (CAMs), thus, increasing safety at junctions [30] or for cyclists [31].

2.4 Vehicle Platooning

A big application use-case for cooperative driving is vehicle platooning. In vehicle platooning, multiple vehicles form a so called *road-train* by following each other with very small safety-gaps [3, 4, 32]. The first vehicle in a Platoon is driven either by either a human or ACC and the following vehicles are driving autonomously by CACC, combining ACC and data from other vehicles received via IVC. Platooning is the fourth stage of highway automation described by Raza and Ioannou [16].

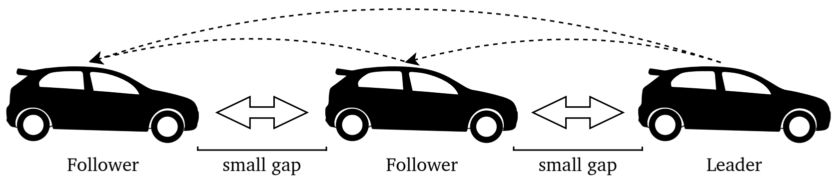

Figure 2.3 – Three vehicles are driving with small safety gaps in a platoon while being automated by Cooperative Adaptive Cruise Control. The arrows depict the measurements of relative distance and speed using RADAR or LIDAR.

In contrast to the scenario from Figure 2.2, Figure 2.3 now depicts a scenario with three vehicles. Moreover, the vehicles are driving with small safety gaps in a platoon while being automated by CACC. As with ACC, the distance and relative speed between vehicles is measured by a sensor and used as input to the system. This is depicted by the arrows between vehicles. Additionally, as indicated by the dashed arrows above the vehicles, this control system uses information it received via IVC from other vehicles, such as driving speed, position and acceleration.

The concept of platooning has been investigated in depth in the literature and in field trials on the road. Well known projects in the field are PATH [3, 8] and SARTRE [9, 10], both of which demonstrated the technical feasibility of stable platooning on the road – certainly limited to a few cars. Ongoing research mainly focuses on improved reliability of the necessary IVC protocols to achieve perfect string stability with guaranteed safety measures [11–13].

Platooning usually assumes freeways or highways as typical scenarios [3, 16]. On freeways, there are many vehicles with large safety gaps between each other, thus, improving the road utilization by decreasing these gaps is desired. Vehicles usually drive on the freeway for some time before exiting and, although not having the same destination, tend to have a similar route to that of many other vehicles. Furthermore, freeways are straight roads with only one direction and multiple lanes, which makes automation and Platoon maintenance certainly more feasible than other more complex road scenarios.

Platooning for Heavy Duty Vehicles (HDVs) or trucks is already implemented by some manufactures such as Volvo, MAN or Daimler [33–35]. Since they typically drive even longer distances than cars and are similar in terms of driving speed and driving capabilities, they have a large potential for fuel savings [36] when driving in platoons.

Studies have shown that Platooning is also useful for normal cars [17], since it has a positive impact on the road utilization, traffic flow, and comfort & safety. Platooning for cars, however, has not yet been deployed at all. In fact, car manufacturers only now are starting to implement IVC technology in their cars [29].

2.4.1 Cooperative Adaptive Cruise Control

To cope with large safety gaps necessary for ACC, CACC uses IVC to get additional information about intended speed changes from other vehicles in the Platoon, thus improving the reactivity of the system. Vehicles periodically send information such as their speed, position and acceleration in wireless beacons. This information then is used to adjust the vehicles cruising speed in order to achieve string stability.

Directly combining ACC and information from the front vehicle (i.e., the preceding vehicle) received via IVC, the desired acceleration of a vehicle, according to

Ploeg et al. [37], can be calculated by

$$\dot{u}_i = -\frac{1}{T}\left(\dot{x}_i - \dot{x}_{i-1} + \lambda\left(x_i - x_{i-1} + l_{i-1} + T\dot{x}_i\right)\right) , \tag{2.3}$$

where $\dot{u}_i$ is the change in acceleration of vehicle with index i, T is the time headway, as described in Equation (2.2), k_p and k_i are tuning parameters and u_{i-1} is the desired acceleration of the front vehicle, received via IVC. Here, T can be as low as 0.5 s [37], which is half of the typical value for ACC on its own.

If, additionally to the information from the preceding vehicle, the information from the leading vehicle is used, a safety gap with constant spacing can be achieved [18, 38]. The corresponding CACC, developed in the PATH project, calculates the desired acceleration by

$$u_i = \alpha_1 u_{i-1} + \alpha_2 u_0 + \alpha_3\left(\dot{x}_i - \dot{x}_{i-1}\right) + \alpha_4\left(\dot{x}_i - \dot{x}_0\right) + \alpha_5\left(x_i - x_{i-1} + l_{i-1} + d_d\right) , \tag{2.4}$$

where u_i is the acceleration of vehicle i, d_d is the desired distance between vehicles in meters, l_{i-1} is the length of the front vehicle and a_i are tuning parameters for the system. The measured inter-vehicle distance (i.e., $x_i - x_{i-1}$) is obtained through the sensor measurements, while acceleration of the leader u_0, speed of the leader $\dot{x}_0$, acceleration of the front vehicle u_{i-1}, and speed of the front vehicle $\dot{x}_{i-1}$ are received via IVC. With this controller, constant gaps down to 6 m [32] or even 5 m [10] are possible.

In addition to the two aforementioned controllers, many other have been developed by researchers in order to improve system behavior regarding string stability, safety, and efficiency [8, 32, 39–45].

2.4.2 Benefits

Driving in platoons brings several benefits. The most obvious benefit is a better utilization of the road due to smaller gaps between vehicles, thus, increasing the road capacity and the traffic flow [7]. Typically, a traffic flow higher than the capacity of the road leads to congestion, shock-waves of traffic and eventually traffic jams [46–48]. Depending on the penetration rate of vehicles equipped with platooning technology on the road, platooning has positive effects on the traffic, i.e., decreased shockwave effects, smoother drive, and an increased average speed [7, 49–51]. Furthermore, smoother speed changes by the autonomous driving system lead to increased comfort for the driver [17, 52, 53] and automation in general leads to increased safety [17].

Another major benefit is also due to small safety gaps: a reduced air drag, which leads to a reduced fuel consumption [6, 54–60], in case of HDV platooning of up to 20 % [36, 61], depending on the distance between vehicles. According to Hucho [62], *"if no other changes are made in a vehicle, the benefits of reduced drag are actually* *threefold: reduced fuel consumption, increased acceleration capability, and increased top speed"*. Then, the change in fuel consumption can be calculated dependent on the change in air drag [62, 63].

The reduced air drag can be seen in Figure 2.4, where Figure 2.4a shows the air drag of a single car and Figure 2.4b shows the air drag of two cars driving with a small gap. As the distance between cars becomes smaller, the air drag behind the first vehicles decreases due to less turbulences. Additionally, the air pressure in front of the second vehicle decreases due to the low pressure zone right behind the first vehicle. This leads to an overall decreased air drag for both vehicles, with the first vehicle in some situations experiencing an even lower drag than the second vehicle [64], as the drag depends on the distance between vehicles as well as their positions in the platoon [65].

2.4.3 String Stability

In order for platooning to work, some challenges need to to be overcome. The most important one is to achieve *string-stability* within the platoon to allow a safe operation of the system.

String-stability describes keeping the distance between vehicles constant and avoid oscillations of this gap due to speed changes of preceding vehicles and other events. Besides keeping the gap small enough to utilize the reduced air drag, it still has to be large enough to allow a safe operation of the whole system in the event of an emergency situation. In order to achieve string stability with such small gaps as used in platooning, feeding the controller with updates from other vehicles (especially the leading and the front vehicle) via wireless communication is critical. For safely maintaining a gap of 5 m, an update frequency of at least 10 Hz is necessary [17]. Fernandes and Nunes [12] have shown that string stability can be

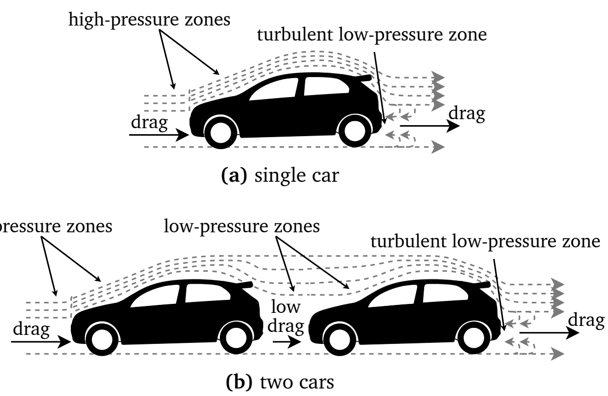

Figure 2.4 – Schematics of vehicular air drag [17], while driving individually and with a small gap to the preceding vehicle.

achieved, if controller updates arrive with a high enough frequency for the control system to react. If the updates are delayed, however, Liu et al. [11] have shown that *"string stability is seriously compromised [...] when the controllers are triggered by the receipt of either the leader vehicle information or the preceding vehicle information"*. Thus, powerful and reliable protocols for the dissemination of these updates are necessary.

Multiple of such protocols have been proposed in recent years. Regular beaconing of a vehicle's information is one approach, however, this can result in a congested channel, reducing the stability of a Platoon [66]. Using a combination of slotted beaconing and transmit power control can greatly improve the performance in crowded scenarios, thus, reducing the load and improving the reliability [66, 67].

In order to reduce channel load even more, dynamic beaconing schemes like *Jerk Beaconing* [13] have been proposed. There, the intervals between the transmission of two beacons are computed dynamically based on changes in acceleration. Furthermore, grouped beaconing helps overcoming channel limits by reducing the number of nodes contending for the channel and improving spatial reuse [68].

In terms of technologies for IVC, there are multiple options: DSRC enables efficient ad-hoc communication without complicated registration procedures [21], whereas cellular technologies like LTE can provide a greater dissemination area and computational performance due to their back-bone network. Using multiple wireless channels (e.g., Control Channel (CCH) and Service Channel (SCH) in IEEE 1609.4 or different TDMA slots in ARIB T109) or even a combination of heterogeneous communication technologies (e.g., DSRC and LTE) can improve network congestion, as the load is distributed. Also alternative communication technologies such as Vehicular VLC (V-VLC) could be used for platooning [69].

Although there are still open issues in maintaining a stable Platoon, the literature and field-tests show that it is not just a theoretical concept but also technically possible and feasible.

2.4.4 Platoon Maneuvers

Beyond platoon management, several additional challenges need to be solved; one of this challenges is *platoon maneuvers*. This includes questions such as *"How can a car join/leave a platoon"* and *"How can platoons be merged"*. Assuming a known set of vehicles that should form a platoon, or a vehicle from an existing platoon wants to leave to exit the highway, coordinated controlled maneuvers among all vehicles are necessary to solve this issue. Moreover, merging and splitting whole or parts of platoons and also lateral changes (i.e., changing the lane) need to be controlled by such maneuvers. This list can be extended by an arbitrary number of other scenarios and situations for further maneuvers; to sum it all up *"platooning is much more than simple car following"* [15].

Maneuvers can be controlled from a centralized point of view, e.g., using infrastructure support and theoretic control laws for vehicles [8, 32]. In contrary, they can be controlled in a distributed manner, where vehicles dynamically react to the environment and actions of other vehicles by using deterministic rules of how they should behave [14]. According to Segata et al. [15], defining application layer protocols to support maneuvers is difficult, as they *"need to be able to identify external events, e.g. interference by other road users, or impairments, e.g. communication faults, and properly react to these, keeping integrity of the system and safety for the drivers"*.

In order to analyze elementary maneuvers needed for platoon management, Segata et al. [15] built a simple application layer protocol for the join maneuver. They show that relatively simple logic can support complex maneuvers, e.g., letting a vehicle join in the middle of a platoon, while guaranteeing that in case of interference and up to 50 % packet loss the maneuver can safely be aborted. To achieve such high robustness, they use application level acknowledgements and claim that *"this implementation is safer than using 802.11p unicast communications"*. They propose their idea toward a modular approach for maneuvers, *"i.e., the development of complex maneuvers by combining smaller sub-maneuvers, aiming to ease development and safety analysis"*.

Amoozadeh et al. [42] developed a protocol for managing maneuvers based on IVC which consists of three basic platoon maneuvers: merge, split and lane-change. Via simulations, they show that several different other scenarios such as joining and leaving can be achieved by using these basic platoon maneuvers. Their protocol can cope with communication loss by using retransmissions of lost messages or switching to ACC.

Liang et al. [70, 71] studied the influence of non-automated vehicle traffic on a merging maneuver of two HDVs via simulation as well as in an extensive experimental study on a public freeway. They show that the surrounding traffic has an impact on the merge maneuver, as other vehicles might drive too slowly and thus delay the merge.

2.4.5 Platoon Formation

Another challenge beyond safe and stable operability of platoons is *platoon formation*. This includes questions such as *"How to form platoons"* and *"Which cars are good candidates to form a platoon (with)"*. Assuming candidate vehicles/platoons are selected by some formation strategy, cars should perform maneuvers to join these candidates, using the aforementioned maneuvers.

Early platoon formation solutions can be grouped into several classes. In one of the early papers, Hall and Chin [72] propose offline formation strategies, which sort vehicles into platoons at the entrance ramp of a highway. Vehicles are grouped according to their destination and enter the highway in a platoon formation when the group consists of enough vehicles. Their main optimization goal is to maximize the platoon size and the time a platoon stays intact. As a second criterion, the destination is used to make sure that platoons can last as long as possible. Following a similar line of thought, other approaches also sort vehicles on the entrance ramp to minimize the total trip time by optimal speed limits and entrance ramp release times [73, 74]. Other concepts looked into optimizing the total fuel consumption for all transport assignments in the scenario, while taking into account fuel savings due to platooning as well as speed changes [75]. The complexity of such centralized optimization has been shown to be NP hard [76].

In contrast to centralized platoon formation, there also have been studies considering distributed approaches. In a very early study, Khan and Bölöni [77] develop a system for ad-hoc convoy formation on freeways. The system continuously evaluates the cost and the possible benefit of forming a platoon with other vehicles in proximity; if successful, it indicates the decision to the driver using an LED to adjust the ACC accordingly. More recently, Liang et al. [78] study fuel-efficient distributed ad-hoc platooning for HDVs by analyzing the optimization problem of pairwise coordination of vehicles. The proposed algorithm for coordination lets the leading vehicle slow down and the trailing vehicle speed up, in order to make the formation process fuel-efficient and keep delivery constraints. Results show that the approach yields significant fuel savings already in the pairwise coordination.

Larson et al. [79] deploy a distributed network of virtual controllers at junctions in the road network. The controllers monitor HDVs approaching these junctions, in order to form platoons with other vehicles in proximity. Using information such as speed, position, and the destination of a vehicle, the controller calculates the cost of adjusting the speed to form a platoon with another vehicle for all approaching HDVs and the corresponding possible fuel savings by doing so. Simulation on the German *Autobahn* road network show that only minor speed adjustments are necessary for a HDV to form a useful a platoon with other vehicles.

Communication is used to coordinate ad-hoc platoon formation in Dao [80]. Here, the system aims at increasing lane capacity and, thus, enhancing traffic throughput by having vehicles on entrance ramps of a freeway communicate with other vehicles and platoons in range to find feasible platooning opportunities. In a more advanced approach, Hobert [81] introduces the possibility to even change platoons. After entering the freeway, vehicles search for platoons and join feasible ones. If no feasible platoon can be found, vehicles can temporarily join a non feasible platoon until they find a better one to which they can switch.

The concept presented by Caballeros Morales et al. [82] is closest to our solution. A distributed clustering algorithm using IVC groups cars according to their destination, speed, and position. The algorithm is executed by every car and forms groups with other vehicles by minimizing their respective deviation, in order to increase lifetime of clusters among the mobility pattern of vehicles. Simulations show that their algorithm performs well in terms of cluster lifetime, cluster-head changes, and the number of cluster re-affiliations.

The aforementioned strategies for platoon formation show that optimal groupings substantially improve the performance gain. Unfortunately, the optimization objectives are quite different, making a comparison becomes infeasible, so that a detailed comparison of centralized and distributed solutions is still missing in the literature. Furthermore, only limited optimization parameters were chosen together with a restrictive set of performance metrics. In this thesis, we go one step further and, besides formally describing the platoon formation problem, we introduce both a centralized and a distributed heuristic. We compare both solutions in detail using a wide range of performance metrics.

2.5 Simulation of Intelligent Transportation Systems

Since first deployments of IVC technologies and ITS applications are on-going, researchers shifted their focus from studying lower communication layer aspects to higher layers, such as ITS and cooperative application protocol design. In order to develop and test such applications, researchers need complete cars equipped with IVC technology, since analytical models are not feasible anymore due to their complexity. In fact, for studying cooperative applications and maneuvers, multiple of such cars as well as driving behavior or even real traffic are necessary. Maintaining a fleet of such IVC equipped cars is way to expensive and too complex as well. Therefore, large-scale studies of such systems are usually done by computer simulation, which has quickly become a tool of choice for many researchers [21]. Simulations allow quick prototyping of protocols and systems by using higher layer programming languages such as C++ and provide tools for debugging and visualization. Having multiple thousands of cars for evaluation of the performance of a protocol under study in large scale environments is easily possible due to the computation capabilities of today's PCs.

In order to get the most out of such a simulation study, one has to choose a useful simulation tool which is easy to use during development and implementation of the algorithms and protocols under study, as well as during result evaluation. Additionally, for simulating ITS, a framework providing features such as IVC, vehicle mobility and traffic is necessary in order to achieve useful results.

Computer networks usually are considered as discrete event systems [83]. Therefore, it is very convenient to simulate these systems with discrete event simulators, such as ns-3[2] or OMNeT++[3].

OMNeT++ is a discrete event simulator for modeling communication networks written in C++ by Varga [84]. It is used in several problem domains and projects, since it easily allows designing and evaluating wired and wireless networks as well as communication protocols. The simulator provides a framework and tools, which can be used to build any type of network simulation that can be modeled with discrete events. In order to simulate wireless networks, MiXiM[4] has been created as a framework for OMNeT++. MiXiM provides *"detailed wireless channel models, wireless connectivity, mobility models, models for obstacles and [...] communication protocols"* [85]. Using parts from MiXiM, the INET framework[5] also provides models for OMNeT++ to simulate IVC, such as for IEEE 802.11p.

For simulating realistic vehicle mobility and traffic, the open-source traffic simulator SUMO [86] provides vehicle definitions, driver models such as the Intelligent Driver Model (IDM) by Treiber et al. [87], and routing algorithms. With SUMO not only vehicular but also human traffic can be simulated in road networks in the scale of a small city up to big scenarios [86].

Veins [88] couples networking from MiXiM as well as mobility from SUMO to serve as a simulation framework for realistically studying VANETs. It is open-source and contains several models for DSRC and IVC, such as IEEE 802.11p [89], IEEE 1609.4 [90] and ARIB T109 [26]. Therefore, it is used in many publications in the vehicular domain. Artery [91], an extension of Veins, additionally provides a model for ETSI ITS-G5.

When simulating cooperative mobile systems such as Platoons, automated longitudinal controllers such as ACC and CACC have to be modeled as well. Fernandes and Nunes [92] implement a new Car Following (CF) model to SUMO in order to support CACC with a constant spacing policy. However, they do not use a network simulator for realistic IVC and only support CACC driven vehicles.

A similar approach is followed with Plexe[6] by Segata et al. [93, 94]. They also extend SUMO with CF models for CC, ACC and multiple CACCs [32, 37, 41, 43]. Building upon Veins, Plexe contains realistic simulation models for IVC and adds functionality for platoon management, such as an initial implementation of the join maneuver [15, 95].

[2]`https://www.nsnam.org/`
[3]`https://www.omnetpp.org/`
[4]`http://mixim.sourceforge.net/`
[5]`https://inet.omnetpp.org/`
[6]`http://plexe.car2x.org/`

Chapter 3

Platoon Formation

EARLY approaches to find candidate cars to construct platoons consider different constraints and formation goals, such as grouping by destination or route, or by fuel efficiency. The general task is similar to clustering cars according to some similarity metric corresponding to the constraints and goal introduced by a formation strategy.

Clustering of vehicles in general has been intensively investigated [96]. According to Zanjireh and Larijani [97], clustering algorithms (for wireless sensor networks) can be sorted into the following two categories: *Centralized*, where a centralized entity in the network runs a clustering algorithm and uses extensive knowledge about all actors in the network to take decisions. In the vehicular context, cellular technologies such as LTE can be used to send information to the central server. *Distributed*, where the clustering algorithm runs on each actor individually and uses information about other actors in the local neighborhood for taking decisions. Therefore, the clustering algorithm has only limited local knowledge about the other actors in the scenario. In the vehicular context, the information can be broadcasted with periodic beacons via wireless communication such as DSRC.

3.1 Problem Formulation

We are using the desired driving speed as a primary similarity metric. However, since is it not useful to join a platoon far away, we also consider the position of the cars as a secondary optimization metric. In order to come up with a formation strategy, we formalize the problem as follows: Let a car be represented by the set

$$\{id, des, pos\} \ , \tag{3.1}$$

where id is the identifier of the car, des is the desired speed of the car, and pos is the current position of the car.

We can now consider platoon formation as the following optimization problem:

$$\forall i : \text{minimize } f_i(x), \quad \forall x \in \Omega_i , \tag{3.2}$$

where Ω_i is the neighborhood of car i (i.e., all cars x, which are in (close) proximity of car i) and

$$f_i(x) = \alpha \cdot d_s(x,i) + \beta \cdot d_p(x,i) , \tag{3.3}$$

determines the cost for car i to join car x, in order to form a platoon; with

$$d_s(x,i) = \|des_i - des_x\| , \tag{3.4}$$

$$d_p(x,i) = \begin{cases} \|pos_i - pos_x\| & \text{if } pos_x > pos_i \\ \infty & \text{if } pos_x \leq pos_i \end{cases} , \tag{3.5}$$

$$\alpha, \beta \in [0,1], \quad \alpha + \beta = 1 , \tag{3.6}$$

and subject to the following constraints:

$$d_s(x,i) \leq p \cdot des_i, \quad p \in [0,1] , \tag{3.7}$$

$$d_p(x,i) \leq r . \tag{3.8}$$

In summary, we try to find the best fitting platoon candidate x for each car i, maximizing their similarity. It is important to mention that the definition from Equation (3.5) only allows joining at the end of a vehicle or platoon.

As an example, consider the scenario depicted in Figure 3.1, where four cars are driving on an arbitrary road with two lanes (e.g., a freeway) and now try to find a platoon. The cars in the example are defined by their set of properties,

$$\{5, 121\,\text{km/h}, 430\,\text{m}\}, \{13, 89\,\text{km/h}, 270\,\text{m}\},$$
$$\{20, 107\,\text{km/h}, 250\,\text{m}\}, \{37, 93\,\text{km/h}, 70\,\text{m}\},$$

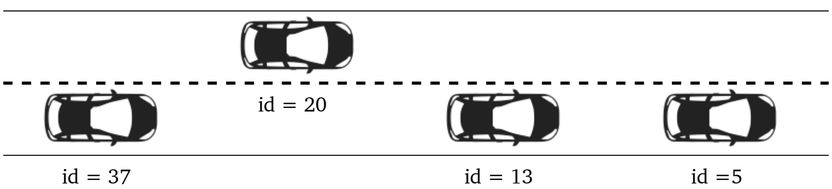

Figure 3.1 – Example scenario: Four cars are driving on a road and try to find a platoon.

and parameters

$$\alpha = 0.6, p = 0.4, r = 400\,\text{m}.$$

By using these properties and parameters, the list of possible platoon candidates and their corresponding cost $f_i(x)$ can be calculated as

$$f_{13}(5) = 0.6 \cdot 32 + 0.4 \cdot 160 = 83.2$$

$$\begin{aligned} f_{20}(5) &= 0.6 \cdot 14 + 0.4 \cdot 180 = 80.4 \\ f_{20}(13) &= 0.6 \cdot 18 + 0.4 \cdot 20 = 18.8 \end{aligned}$$

$$\begin{aligned} f_{37}(5) &= 0.6 \cdot 28 + 0.4 \cdot 360 = 160.8 \\ f_{37}(13) &= 0.6 \cdot 4 + 0.4 \cdot 100 = 42.4 \\ f_{37}(20) &= 0.6 \cdot 14 + 0.4 \cdot 180 = 80.4 \ . \end{aligned}$$

From the list of possible candidates and their corresponding costs, the optimal solution minimizing the overall cost is

$$\begin{aligned} f_{37}(13) &= 42.4 \\ f_{20}(5) &= 80.4 \ , \end{aligned}$$

as selecting a candidate pair blocks both involved cars, making them unavailable for further selection.

Since a car can only be in one maneuver at the same time, at most two maneuvers can be ongoing in parallel. After these maneuvers are finished, the cars in the scenario will be grouped into two platoons: $\{13, 37\}$ and $\{5, 20\}$.

In order to solve this optimization problem optimally, a mathematical solver is necessary. However, due to computational and time constraints, we use a heuristic to select feasible candidates which follows a greedy approach: We calculate the cost $f_i(x)$ for all cars in the neighborhood which do not violate the constraints given by Equations (3.7) and (3.8) and add an entry for them to a list of possible matches. Then, we select the candidate x with the smallest cost (i.e., deviation in speed and position) from this list and let the searching car i join this selected candidate x.

If the join maneuver is successful, car i afterwards is part of a platoon with car x (which was just formed or x was already part of). Once cars become platoon members, they do not leave the platoon until they reach their destination. In this study, every car has the same destination. Therefore, the whole platoon sticks together until this destination is reached. Also, in comparison to the strategy by Hobert [81], cars cannot change their platoons after a successful join, as they stop searching once they become a platoon member.

3.2 Centralized Approach

In our centralized approach, the optimization problem is solved for every car in the scenario at the same time. Since the central server has global knowledge about all cars and their corresponding information, it can use the information to make decisions about platoon assignments. We assume that this global knowledge is collected by means of an infrastructure based network such as LTE. Using this knowledge, the aforementioned greedy approach can be executed for all cars at the same time.

We use the heuristic given in Algorithm 3.1 to create the list of possible matches. An entry $\{id_i, id_x, f_i(x)\}$ in this list contains cars i and x and the cost for letting car i join car x. Note that this is not symmetric as the cost from car i to x might not be the same as from car x to i.

Once all possible matches and their costs are computed, we use Algorithm 3.2 to select the best match for every searching car i to let it join a candidate car x. In particular, we select the match with the smallest deviation $f_i(x)$ and remove all entries which contain cars i and x. This heuristic is greedy from the perspective of a searching car i as it denies other searching cars to join the same car x later in the process.

Require: meta info of all cars in the scenario
  for all cars i in the scenario **do**
    if i **not** in platoon **and** i **not** in maneuver **then**
      for all cars x in the scenario with $x \neq i$ **do**
        if (x in platoon **and** x **not** leader) **or** x in maneuver **then**
          next;
        end if
        if $d_s(x,i) > p \cdot des_i$ **or** $d_p(x,i) > r$ **then**
          next;
        end if
        add $\{i, x, f_i(x)\}$ to list of possible matches
      end for
    end if
  end for
Ensure: list of possible matches list$(\{i, x, f_i(x)\})$

Algorithm 3.1 – Pseudocode describing the heuristic for finding candidate pairs in the centralized approach

Re-considering the example from Figure 3.1, the centralized heuristic selects the following matches out of all possible ones:

$$f_{13}(5) = 83.2$$
$$f_{37}(20) = 80.4$$

After selecting car 13 to join car 5, both cars 13 and 5 are blocked, thus, leaving no match for car 20. Car 37 also cannot join car 13, hence the heuristic selects car 37 to join car 20. Although this approach also produces two platoons after successful finishing of the join maneuver, it does not compute the aforementioned optimal solution. However, as we will show in the evaluation, the heuristic performs quite well for the global scenario.

3.3 Distributed Approach

In our distributed approach, every car i has to execute the aforementioned greedy heuristic individually. In order to run any kind of selection algorithm, cars first of all have to become aware of other cars in their neighborhood. Therefore, all cars are transmitting their meta information via periodic beacons using IVC protocols such as IEEE 802.11p and maintain this data in a local neighbor table.

Using the entries in the neighbor table, the heuristic given in Algorithm 3.3 is executed to prepare the list of possible matches. Then, a heuristic very similar to Algorithm 3.2 is used to select a candidate car x with the smallest cost to join.

Conceptually, the same matches as in the centralized approach are selected. However, the selection of possible matches is limited to the restricted nature of the neighbor table and, therefore, depends on the time the heuristic is evaluated. Also, the quality of the heuristic now depends on the quality of the neighbor information, which depends on the used beacon protocol [98]. In comparison to the centralized

Require: list of possible matches $\text{list}(\{i, x, f_i(x)\})$
  for all unique cars i in the list of possible matches **do**
    $m \leftarrow x \in \text{list}(\{i, x, f_i(x)\})$;
    if $\|m\| > 0$ **then**
      $b \leftarrow \{x | \min f_i(x), x \in m\}$ {Select best candidate x}
      remove all entries containing cars i and x
      let i join b
    end if
  end for
Ensure: pairs of cars to perform join maneuver

Algorithm 3.2 – Pseudocode describing the heuristic for selecting the best candidate in the centralized approach

approach, the big disadvantage is that the information might not be up-to-date or even obsolete. If cars are in a maneuver or even in a platoon since their last broadcast, any join maneuver started with them will be aborted. In the centralized approach, we assume the information always to be up-to-date, thus, cars which are not applicable anymore are not selected in the first place.

3.4 Model Implementation

We implement all algorithms in the simulation tool Plexe [93, 94]. Plexe can simulate platoons, utilizing SUMO [86] for simulation of road traffic and Veins [88] for simulation of realistic wireless communication and, thus, provides all relevant functionality for maintaining platoons.

3.4.1 Formation Algorithms

We implemented the centralized approach in a global module in the scenario, that directly accesses the cars' information (e.g., speed and position). Based on this information, it runs the heuristics described by Algorithms 3.1 and 3.2 and computes join tasks which are assigned to the involved cars. The cars then start a join maneuver with their corresponding platoon candidates. For the distributed approach, the heuristics described by Algorithms 3.2 and 3.3 are implemented in the application layer module of every car.

Cars send platoon advertisements via wireless beacons, including information about themselves as well as the platoon they are part of. This information is stored and maintained in a 1-hop neighbor table, which is used by the heuristic. Additionally, cars periodically broadcast their speed and position in cooperative awareness messages, later used for platoon maintenance. Due to the transmission range, cars conceptually only have local knowledge about the scenario, i.e., about cars in wireless transmission range.

Require: neighbor table storing the information of neighboring cars x for a fixed car i
  for all cars x in the neighbor table **do**
    if $d_s(x,i) > p \cdot des_i$ **or** $d_p(x,i) > r$ **then**
      next;
    end if
    add $\{i, x, f_i(x)\}$ to list of possible matches;
  end for
Ensure: list of possible matches $\text{list}(\{i, x, f_i(x)\})$

Algorithm 3.3 – Pseudocode describing the heuristic for finding candidate pairs in the distributed approach

After the heuristic selects a candidate, the car tries to join this candidate by executing a join maneuver, using control messages via wireless communication as well. This join maneuver is performed by Plexe, which we extended to support dynamic joining to arbitrary vehicles.

3.4.2 Join Maneuver

In order to realistically simulate platoon formation, we need to consider a proper join maneuver. Plain Plexe already provides a prototype implementation of such join maneuver by Segata et al. [15], which was, however, not applicable to our use case. Therefore, we re-worked this prototype implementation to support dynamic joining to arbitrary vehicles in the simulation, and all of the different situations that can occur during such a maneuver. In this process, we extended the Finite State Machines (FSMs) of the initial prototype.

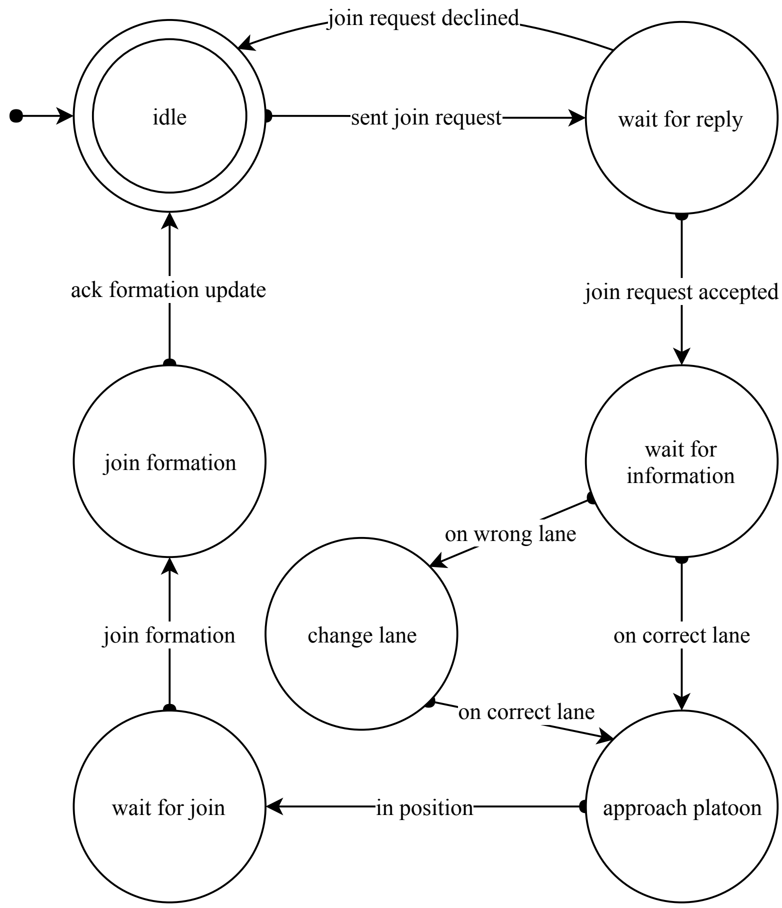

Figure 3.2 – FSM describing the behavior of a joining car in the extended join maneuver implemented in Plexe. Possible timeouts are omitted for readability.

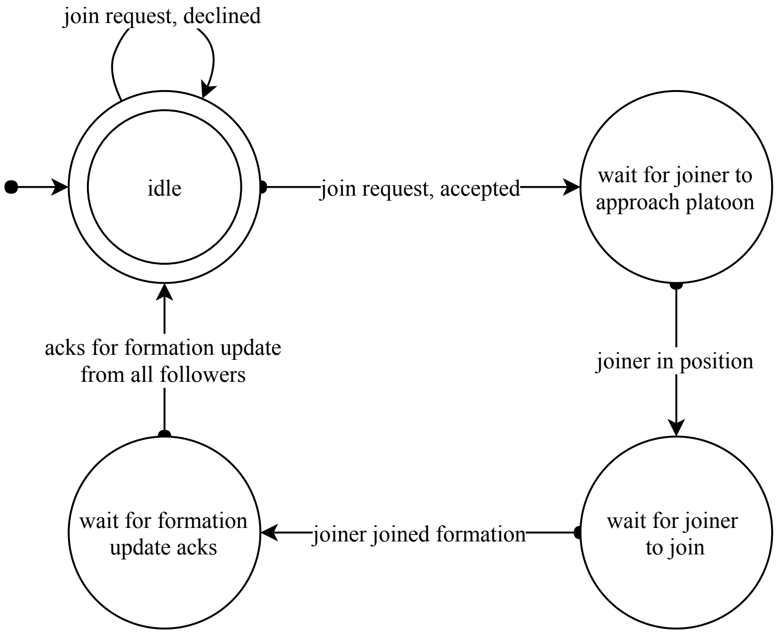

Figure 3.3 – FSM describing the behavior of a leading car in the extended join maneuver implemented in Plexe. Possible timeouts are omitted for readability.

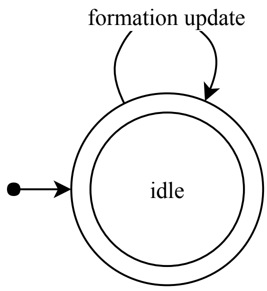

Figure 3.4 – FSM describing the behavior of a following car in the extended join maneuver implemented in Plexe. Possible timeouts are omitted for readability.

Figures 3.2 to 3.4 show the FSMs describing the logic of the extend join maneuver for every role a vehicle in a platoon can be in (i.e. leader, follower, joiner).

Initially, every car is in the *idle* state. Then, a vehicle which wants to join a platoon (or another individual vehicle) sends a join request to the leading vehicle of the (potential new) platoon and waits for a reply. The request can be accepted or declined, in any case, i.e., assuming successful transmissions, the vehicle which sent the request gets a reply from the leader.

Upon acceptance, the leading vehicle additionally sends information about the platoon such as driving speed and position to the joining vehicle and waits for it to get into position to join the formation. After receiving the information about the platoon, the joining vehicle checks if it is already on the same lane as the platoon it wants to join and changes the lane if necessary. Once it is on the correct lane, it starts to approach the platoon by using the information from the leading vehicle and from the broadcast-beacons of its intended front vehicle (i.e. the currently last platoon member).

As soon as the joining vehicle has approached the platoon, i.e., it is close enough to switch from ACC to CACC, it informs the leading vehicle about its readiness. An additional message for achieving consensus about the platoon parameters is sent from the leading vehicle, allowing the joining vehicle to actually join the formation and switch to CACC. Once this is done, the joining vehicle sends a confirmation and switches its role to being a following vehicle.

Now, the leading vehicle has to inform all members of the platoon about the new member. It does so by sending a formation update message, which has to be acknowledged by every member of the platoon (including the recently joined vehicle). Once all acknowledgements are received by the leading vehicle, the whole maneuver is complete.

During a join maneuver, there are many different situations that may lead to an erroneous state of the system. The following list, therefore, gives a brief overview of abort causes, which we use to abort the maneuver in such erroneous situations:

- The response from the leading vehicle does not arrive in time (probably due to network congestion).
- A car is on a different lane than the platoon and, therefore, has to change to a different one, but the lane change takes too long (e.g. due to traffic).
- In contrary to the initial check of the system or due to an incorrect lane change, the car still is on the wrong lane when approaching the platoon.
- While approaching the platoon, some other car merges onto the lane of the joining vehicle, between it and the platoon.
- Approaching the platoon takes to long (e.g., due to traffic).
- The joining car is too close to the platoon to properly finish the maneuver. For instance, the car might initially be next to or in front of the leader (on a different lane).
- The whole join maneuver takes too long (i.e., from the leader's perspective).
- The maneuver is aborted by the platoon leader via an abort message.

Additionally to the aforementioned events, the following situations can occur. These, however, do not lead to an immediate abort of the join maneuver.

- Maneuver control messages are received twice due to the acknowledgment of the unicast transmission got lost and the sender re-transmits the original message.

- Due to channel congestion, an abort message can not be sent, thus, the maneuver partner continues with the maneuver until a timeout is triggered.

If any of the aforementioned situations occurs, the maneuver is aborted and the FSMs are reset to their initial state.

3.4.3 Platoon Management

So far, Platoon management in Plexe is static, as platoons are configured a priori to a simulation and, upon simulation start, cars are placed at the correct position and statically assigned to a corresponding platoon. These platoon assignments and configurations are done within the *PositionHelper* module of each car in the simulation and a global singleton module called *TrafficManager*.

Figure 3.5 shows a schematic of a car module in Plexe. It consists of multiple modules, arranged in layers similar to the Open Systems Interconnection (OSI) model, that provide different functionality of a platoon car. The *Mobility* module as

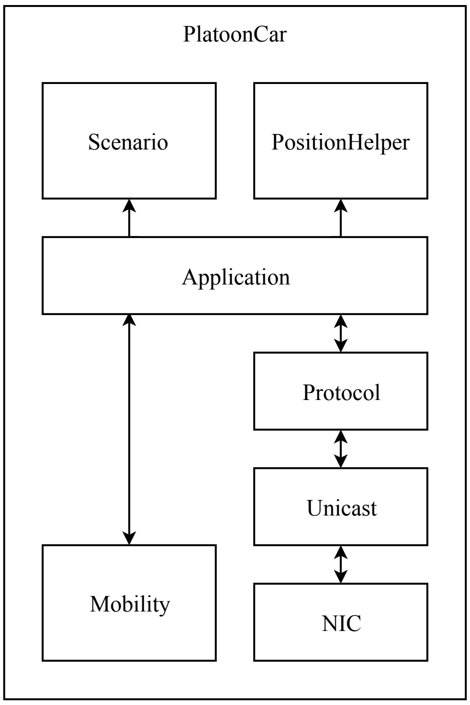

Figure 3.5 – Schematic of a car module in Plexe. Multiple modules, arranged in layers, provide different functionality of a platoon car.

well as the part of Plexe which is included in SUMO, provide engine and mobility and platooning functionality, such as different CACC implementations mentioned in Section 2.5. The *NIC* module provides realistic IVC functionality, e.g. IEEE 802.11p, and the *Unicast* module allows to have acknowledged unicast transmissions. The *Protocol* module provides functionality for periodically broadcasting beacons, including different beaconing protocols mentioned in Section 2.4.3. The *Application* module contains the application logic of the protocols under study, such as our formation algorithms. The *PositionHelper* module contains information about the platoon of a vehicle, such as its position within the platoon. The *Scenario* module contains the configuration for simulation studies and scenarios.

In our study, platoons shall be formed only during run-time, based on the aforementioned formation strategies: Once a fitting platoon is selected, the car should join this platoon and switch its controller to CACC for autonomous control. To allow the cars to dynamically switch from ACC to CACC and being maintained in their corresponding platoon, a new and dynamic version of the aforementioned *PositionHelper* module only maintains information of the local platoon a vehicle is in. Therefore, the new version is called `LocalPlatoonPositionHelper`. Additionally, a generic platooning application, called `GeneralPlatoonApplication`, serves as a base for the join maneuver and our formation algorithms, as it provides general functionality for platooning and maneuvers. Future work in terms of formation logic as well as maneuvers is supposed to be built upon this base as well.

Chapter 4

Evaluation

We evaluate and compare both the centralized and the distributed algorithm in an extensive set of simulations using Plexe. Additionally, we add a baseline scenario without platoon formation. We pick several metrics, some of which are also used in other studies, to understand the impact of platoon formation as such and to show the differences between the centralized and the distributed algorithm. In general, we assume platoon control as stable and do not further investigate CACC properties such as string stability.

4.1 Simulation Setup

We use a freeway scenario for our simulation as shown in Figure 4.1. The freeway has a length of 30 km and contains four lanes. It has additional entry and exit lanes connected to a road with one lane, which is used as spawn point for vehicles. In the simulation, cars only spawn at the first entry and drive to the end of the freeway (i.e., a trip of 30 km). The most relevant mobility parameters are summarized in Table 4.1.

Figure 4.1 – Screenshot of the simulation scenario. The red car is approaching the entrance ramp of the freeway while two other cars are performing a join maneuver (the green car is joining the purple one).

Table 4.1 – Simulation parameters for mobility and road network

Parameter	Value
Freeway length	30 km
Number of lanes	4
Spawn position of vehicles	First entry ramp
Destination	End of the freeway
Max acceleration	$2.5\,\mathrm{m/s^2}$
Max deceleration	$9.0\,\mathrm{m/s^2}$
Vehicle length	4 m
CF model	ACC and CACC [32]
Lane Change (LC) model	LC2013 [99], max. safety
Desired speed v_d	$U\,(80, 130)$ km/h
Min speed $v_{\min}$	0 km/h
Max speed $v_{\max}$	140 km/h
Driver imperfection σ	0.5
Driver's desired minimum headway τ	0.5 s
ACC headway T	1.2 s
CACC desired gap d_d	5 m [10]
CACC bandwidth ω_n	0.2 Hz
CACC damping ratio ξ	1
CACC weighting factor C_1	0.5
Arrival traffic	$B\,(1, 0.5) \rightarrow 2000$ veh/h
SUMO update interval	0.1 s
ACC headway for approaching T_{join}	$\frac{1}{2} \cdot T = 0.6\,\mathrm{s}$
Response timeout	5 s
LC timeout	20 s
Approach timeout	60 s
Maneuver timeout (leader)	$20\,\mathrm{s} + 60\,\mathrm{s} + 5\,\mathrm{s} = 85\,\mathrm{s}$
CACC switch threshold	$1.5 \cdot T_{\text{join}} \cdot v$

Table 4.2 – Simulation parameters for formation logic

Parameter	Value
Tick rate for platoon advertisements	1 Hz
Tick rate for centralized heuristic	1 Hz
Tick rate for distributed heuristic	1 Hz
Valid time for neighbor table entries	2 s

As soon as a car reaches the entrance ramp and merges onto the freeway, it starts advertising itself as a possible platoon candidate and begins searching for existing platoons and other cars to form a platoon with. Additionally, cars periodically broadcast their speed and position in cooperative awareness messages, later used for platoon maintenance. We use IEEE 802.11p for both the join maneuver and the neighborhood management. After the heuristics described in Chapter 3 selected a candidate, the car tries to join by executing the join maneuver. We use the aforementioned application layer unicast protocol on top of IEEE 802.11p to have acknowledged communication during the join maneuver. To simplify the simulation study, we generally assume that our platoon formation algorithm (besides the static beacons for platoon management) is the only application which sends messages and, thus, creating network traffic. Due to this fact, only very little channel load is introduced (i.e., around 5 %), hence, we do not report about this in greater detail.

Table 4.3 lists simulation control parameters, we use for the simulation. We run our simulation for 2700 s, which is twice the minimum time a car driving the slowest desired speed (i.e., 80 km/h) needs to reach the end of the freeway. We use the first half of this simulation time as a warm-up period and ignore all results in this interval. Table 4.3 also lists the different values we use for studying the tuning parameters of our formation strategy. We repeat each combination 10 times for both approaches (i.e. centralized and distributed) and the base line scenario (i.e. without formation).

4.2 Simulation Results

In the following, we report on the results of our extensive simulation study which we described in Section 4.1. We present data according to different metrics, following the process of platoon formation from selecting candidates until joining platoons and using potential benefits of platooning. We compare the performance of both approaches we described in Chapter 3, pointing out their respective advantages and weaknesses.

Table 4.3 – Simulation control parameters and values for parameter study

Parameter	Value
Simulation time	2700 s
Warm-up period	1350 s
Repetitions	10
Max. concurrent vehicles	500
deviation: Deviation from desired speed	0.1 to 0.3, step 0.1
range: Deviation in position	200 m to 1000 m, step 400 m
alpha: Weight of speed deviation	0.0 to 1.0, step 0.2

4.2.1 Number of Platoon Candidates

The found candidates metric counts the number of possible candidates for platoon formation as identified by the Algorithms 3.1 and 3.3 for a single car. The higher the value, the more similar cars are known to the respective algorithm and the more cars can be used to identify the one with highest similarity (i.e., lowest cost). The filtered candidates metric counts the number of possible candidates for formation that do not violate any constraints but are currently in a maneuver, thus, not being useful platoon candidates. Only the centralized approach has the required information available to filter candidates. Naturally, filtering candidates decreases the number of found candidates. We expect the centralized approach to find more possible candidates for platoon formation for each car due to its overall knowledge of the scenario. In particular, it is aware of all cars and their respective properties.

The average number of candidates found by the approaches for every car is shown in Figure 4.2. As can be seen, in contrast to our initial expectation, the centralized approach finds less possible candidates per car than the distributed approach (the median is only 0.8 in comparison to 1.8). Moreover, when considering the 95th percentile where 2.7 candidates in comparison to 4.7 were found. For a small number of cars (i.e., 1 %), the centralized approach, however, does find more candidates.

To explain the contrary effect of a higher number of candidates for the distributed approach, we have to look at the cars which are filtered and therefore not considered as candidates. Cars technically not violating the constraints of the optimization problem defined by Equations (3.7) and (3.8) are filtered, if they are already in a maneuver, thus, not being applicable for another one. The distributed approach does not have the corresponding knowledge and, thus, cannot filter candidates in the aforementioned sense.

Figure 4.3 shows the average number of candidates filtered by the approaches for every car. As expected, the corresponding data shows that no candidates are filtered

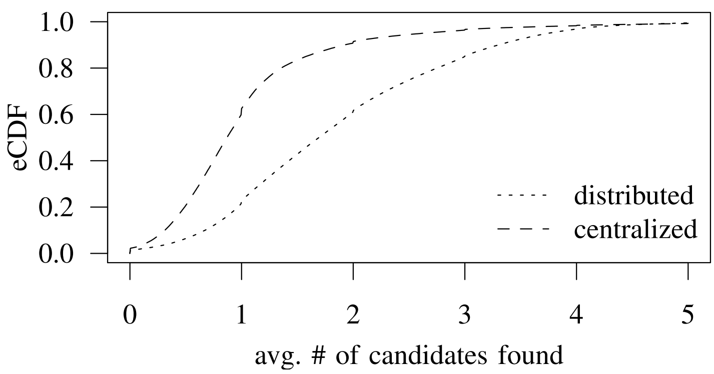

Figure 4.2 – eCDF showing the average number of candidates which are found by the platoon formation strategy in each iteration per car

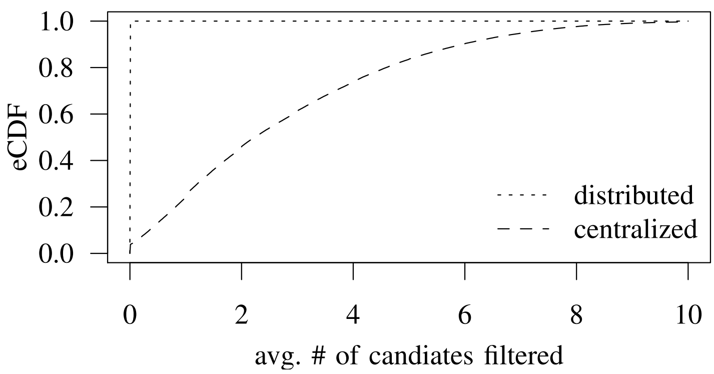

Figure 4.3 – eCDF showing the average number of candidates which are filtered by the platoon formation strategy due to knowledge about the maneuver state in each iteration per car

by the distributed approach. In the centralized approach, however, typically (50th percentile) 2.1 cars, which *do not* violate the original constraints, are filtered per car – even 8.8 cars in the 99th percentile. This shows that the centralized approach indeed finds more platooning opportunities in general because from the perspective of a single car, it is aware of more (i.e., all) other cars. Nevertheless, many of those candidates are filtered because they are already involved in maneuver. Additionally, the centralized approach removes cars involved in already selected platoon assignments in the same iteration step from the list of possible matches, reducing the average number of candidates per car even more. The distributed approach in general finds less candidates, because of its limited awareness of other vehicles due to neighboring beacons and transmission range. However, candidates are neither filtered (because they are in a maneuver already and, therefore, would decline a join request anyhow) nor are the selected candidates unique among different vehicles.

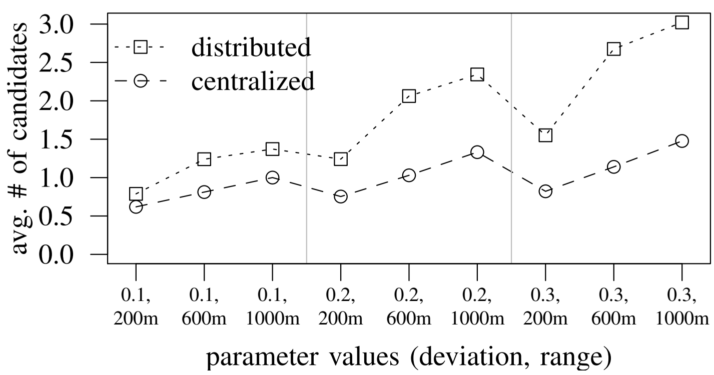

Figure 4.4 – Plot showing the average number of candidates which are found by the platoon formation strategy in each iteration per car. We plot different combinations of values for parameters *deviation* and *range*.

Besides different knowledge of the approaches and, therefore, filtered candidates, the number of found candidates is impacted by different parameters for our heuristics, as listed in by Table 4.3. Figure 4.4 shows the average number of candidates found for different combinations of parameter values. Besides the already discussed effect of the distributed approach always finding more candidates, it can be seen that less restrictive constraints increases the number of candidates the algorithms find. This is expected, as we increase the allowed deviation in speed (i.e., from 10 % to 30 %) and the range range to look for candidates (i.e., from 200 m to 1000 m). Interestingly, the increase in range from 600 m to 1000 m brings less improvement than the increase from 200 m to 600 m in the distributed approach. In the centralized approach, however, the impact of both increases is equal.

When increasing the weight for the speed deviation α, the deviation from the desired speed becomes more and more severe, as its impact on the total cost increases. This also reduces the impact of the deviation in position, thus, allowing far away neighbors to be selected more often. However, even with $\alpha = 0.5$ both deviations do not impact the cost equally, as we use absolute deviations (i.e., in km/h and m) and the deviation in position typically has higher values than the deviation in speed. Therefore, the impact of α on the number of found candidates is negligible and not shown in this study.

4.2.2 Join Maneuver

The number of attempted joins helps understanding the success of the join maneuvers. Whenever a candidate is selected by one of the heuristics, the searching car sends a message to the candidate to request the start of the join maneuver. Independent of the outcome of this message, that is whether it is positive, negative, or no response at all is received, it is counted as an attempted join maneuver.

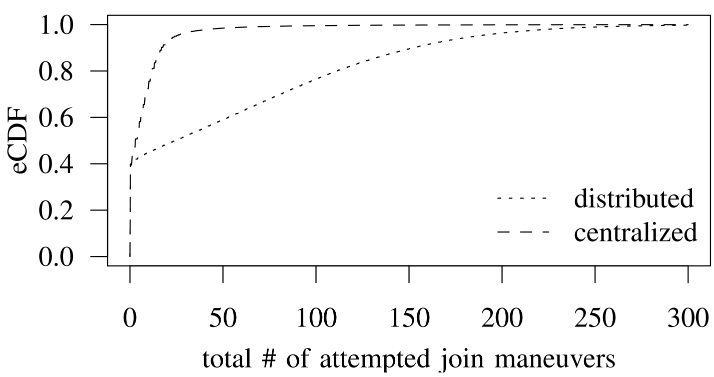

Figure 4.5 – eCDF showing the total number of attempted join maneuvers of per car

Once a platoon assignment for a car is created (i.e., a candidate to join has been selected), the car attempts a join maneuver with the selected candidate by sending a join request. Figure 4.5 shows the total number of such attempted join maneuvers per car. It is evident that the effect of more found candidates has a direct impact on the number of attempted join maneuvers. Trying to join candidates which are not applicable anymore because they are already in a maneuver, leads to a much higher number of total attempted join maneuvers per car in the distributed approach. Additionally, in the centralized approach, already selected cars by the heuristic in an earlier iteration of the loop described in Algorithm 3.2 are removed from the list of possible candidates and, thus, are not applicable for joining anymore. This leads to an even lower number of attempted join maneuvers for the centralized approach, typically (i.e., 50th percentile) 3 in comparison to 24 and, in the 99th percentile, 65 in comparison to 252 for the centralized, and the distributed approach, respectively. Interestingly, in both approaches almost 40 % of the cars never get a single platooning opportunity and, thus, do not attempt a join maneuver at all.

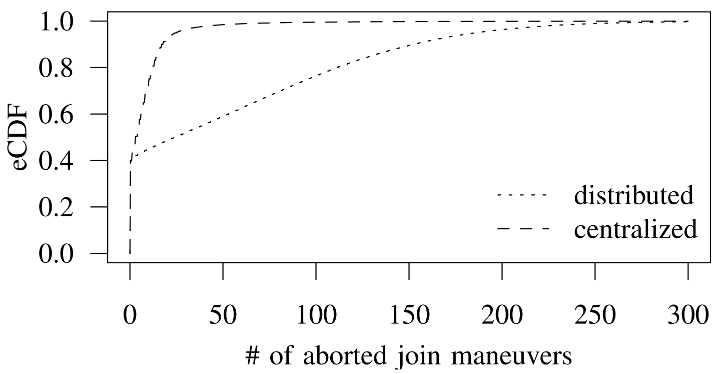

Figure 4.6 – eCDF showing the total number of aborted join maneuvers of per car

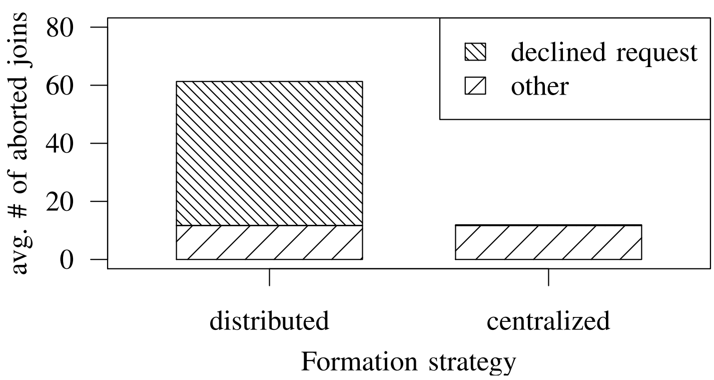

Figure 4.7 – Bar plot showing the average number of aborted join maneuvers of per car

When looking at the high numbers of up to 500 (and more) attempted join maneuvers per vehicle in the simulation, and the fact that vehicles cannot change or leave a platoon, once they become a member, it is clear that many maneuvers do not succeed and are aborted. Most importantly, the join request could be aborted, particularly because the car is already in a join maneuver with another car. Figure 4.7, therefore, shows the average number of aborted join maneuvers per car and different abort causes; causes other than being declined are grouped in *other*. Aborted maneuvers occur in both approaches, being caused by various reasons, as described in Section 3.4.2. In the distributed approach, we see that the majority of aborts is caused by declines of the join request by the leading vehicle. This is because the distributed approach always selects the candidate with the smallest cost, independent from many times the join already failed, and retries to join that candidate until the maneuver is completed successfully.

4.2.3 Platoon Size

We use the number of cars in a platoon to describe the ratio of successful platoon formations. If a car does not find a feasible platoon candidate and, therefore, is not able to become a platoon member, it will not be in a platoon when reaching the destination. Since a platoon stays intact once it has formed, and it only can get more members over time, we consider this value at the end of the scenario. The results are shown in Figure 4.8.

As expected, the baseline shows that all cars arrive as individuals. About 41 % in the centralized and 35 % in the distributed approach, respectively, have not joined a platoon at the end of the scenario. This is either due to not getting an opportunity or due to not finishing the join process. In both approaches it may take some time until cars are in a platoon. The centralized approach leads to smaller platoons (on average, 2.14 cars per platoon), whereas the distributed solution tends to form larger platoons (on average 2.47 cars per platoon). This is due to the fact that the

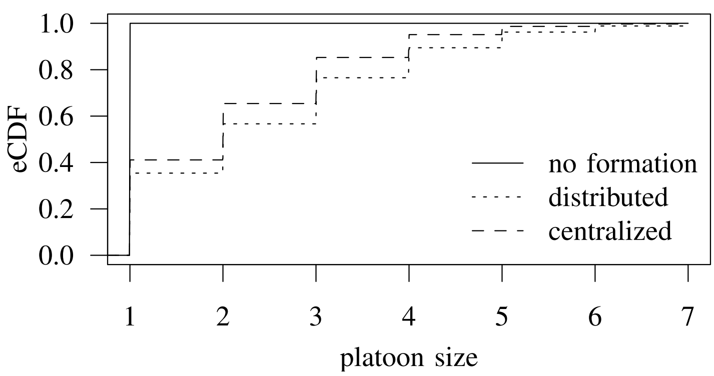

Figure 4.8 – eCDF showing a car's platoon size when reaching its destination

distributed algorithm does not pick a different candidate if the best one is blocked. Therefore, multiple cars eventually join the same platoon, thus, leading to longer platoons. Also, it may take longer to form a platoon with the centralized solution, as the optimal fit may be farther away.

4.2.4 Deviation from Desired Speed

The main optimization goal in our strategy is the desired speed, thus, the deviation from it is of particular interest. The smaller the deviation from the desired speed, the better. The results are shown in Figure 4.9.

The deviation of desired speed is a constraint for considering cars as possible candidates, being simulated at discrete values of 10 %, 20 % and 30 %. Thus, the maximum is at 30 %. As more cars are in a platoon in the distributed approach, more cars deviate from their desired speed to form the corresponding platoon (42 % in comparison to 37 % in the centralized case).

When considering the absolute deviation as well, as shown in Figure 4.10, an additional effect can be seen. Not only do more cars deviate and to a bigger extent in

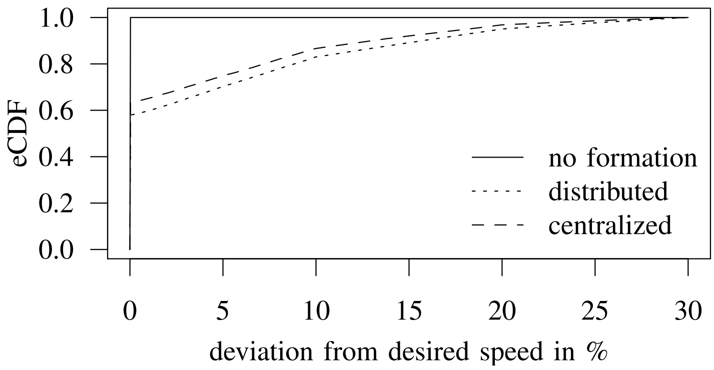

Figure 4.9 – eCDF showing the relative deviation from a car's desired speed when reaching the destination

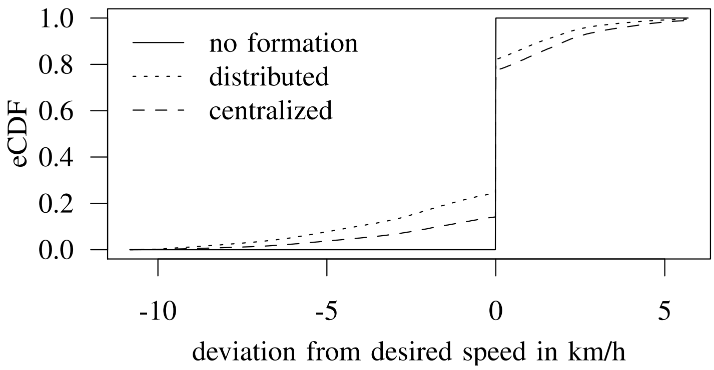

Figure 4.10 – eCDF showing the absolute deviation from a car's desired speed when reaching its destination

the distributed approach, they also tend to deviate more negatively, hence, decreasing their initial speed. On the 1st percentile, cars have to decelerate by −9.2 km/h in the distributed and by −7.8 km/h in the centralized approach, respectively. This is in contrast to the 99th percentile, where cars have to accelerate only by 4.75 km/h and by 5.69 km/h, respectively. On average, cars have to slow down by −0.6 km/h in the distributed case compared to speeding up by 0.01 km/h in the centralized approach.

4.2.5 Happiness

The happiness of a vehicle indicates how happy a vehicle is with its current platoon situation, assuming that all cars want to do join a platoon in order to make use of the benefits such as fuel savings. We calculate it by:

$$h = \left(1 - \frac{d_s(des, cur)}{des}\right) \cdot m \ , \tag{4.1}$$

where des and cur are desired and current speed of the car, respectively, $d_s(i, x)$ from Equation (3.4) is the absolute difference in speed and m is the number of members in the same platoon.

It is difficult to determine the quality of a platoon considering a single metric. Therefore, we us the happiness to measure this quality, as it combines multiple properties. On one hand, it focuses on the driving speed aspect, since drivers have to be willing to compromise in terms of their driving speed and, thus, the travel time in order to form platoons with other vehicles. On the other hand, the size of the platoon is included in the metric. The longer a platoon is (i.e., the more members a it has), the more cars can benefit from the potential benefits, which are described in Section 2.4.2.

As an example for this metric, consider the following examples:

1. If a car has a desired speed of 100 km/h and currently is driving at a speed of 100 km/h without being in a platoon, its happiness is 1. An individually driving car is considered to be in a platoon with a length of 1.
2. If that car now is driving at only 80 km/h, its happiness is $h = \left(1 - \frac{20}{100}\right) \cdot 1 = 0.8$.
3. If this car now is driving in a platoon with 4 members, its happiness is $h = \left(1 - \frac{20}{100}\right) \cdot 4 = 3.2$.
4. If a car is driving with a speed deviation of 50 % and is in a platoon with 2 members, the happiness is $h = (1 - 0.5) \cdot 2 = 1$, similar to the first case.
5. If a car is driving its exact desired speed and is in a platoon with 4 vehicles, the happiness is 4.

These examples show that even a deviation from the desired speed can be compensated for, if the vehicle is in a platoon with many vehicles. Being in a platoon (of at least 2 vehicles) always makes a vehicle "happier" because the platoon size has a higher weight than the deviation from the desired speed. In a long platoon, many vehicles benefit from platooning, as they are subject to a lower drag in the front and in the back. Also, only a few vehicles still have a high drag in the front (i.e., the leading vehicle) and a high drag in the back (i.e., the last vehicle in a platoon). Furthermore, if the vehicle drives exactly at its desired speed, its happiness can only be bigger or equal to 1, as the number of members in a platoon serves as a multiplier.

We consider the happiness of a car at the end of its lifetime, meaning when it reaches it's destination. Since cars stay in their platoon once they become a platoon member, the value of this metric is monotonically increasing towards the destination of the cars. The speed deviation does not change (unless the platoon has to decelerate due to traffic) and the number of platoon members can only increase.

We show the happiness of the cars in the simulation in Figure 4.11. As this metric contains the speed deviation and the platoon size, it is impacted by both individual metrics. However, since the platoon size has a bigger impact due to bigger individual numbers, it is more heavily impacted by the size, as can be seen in the eCDF. Besides cars having a happiness of 1 without formation, due to the aforementioned fact, the distributed approach leads to a higher happiness, as expected. On average, the happiness of cars for this approach is 2.3 in comparison to 2.0 for the centralized approach, the 99th percentile is 6 in comparison to 5.08.

Here, the big advantage of the distributed approach can be seen. Since we assume that every car wants to participate in platooning in order to use its benefits, as described in Section 2.4.2, and with longer platoons more vehicles can benefit, longer platoons are considered as better. However, in order to do platooning, every vehicle has to make some compromises, for example in the desired travel speed (which is our primary similarity metric). It can be seen that slightly higher deviation

Figure 4.11 – eCDF showing a car's happiness when reaching its destination

in travel speed, which is bad if considered individually, can be mitigated by a platoon with many members. Therefore, all of its members are happier in comparison to a small deviation within a smaller platoon. A lower deviation leads to an even higher happiness (considering the same platoon size).

4.2.6 Travel Time

Looking at the travel time, the effects of the deviation from the desired speed can be seen. When merging onto the freeway, every car estimates the time it is going to travel to its destination, assuming a constant speed at the desired value. Upon arrival, cars also record their real travel time, calculating the travel time ratio. We use this metric to show the impact of platooning on the travel time. Cars have to make compromises when they want to do platooning with other vehicles. One of these compromises is to drive at a speed different to their desired one, thus, influencing their travel time. Also, join maneuvers can have an impact on the travel time.

As shown in Figure 4.12, the baseline is almost always at 100 % and only deviates to slower speeds due to traffic. When platooning is enabled, speed deviations in both directions can be observed. During the join process, the car can be faster than its desired speed to close the gap to the platoon. During the trip, the speed can divert from the desired speed both positively as well as negatively. There is only a slight difference between the centralized and the distributed platoon formation approach visible. On average, the distributed case shows a deviation to 104.36 %, whereas the centralized approach leads to a deviation to 102.61 %. Thus, platoons tend to be a bit slower than the desired speed.

In order to understand these effects in more detail, we also look at the platoon time ratio, i.e., the time a car spends in a platoon over the total travel time. The results of this ratio are shown in Figure 4.13. It is slightly larger for the distributed

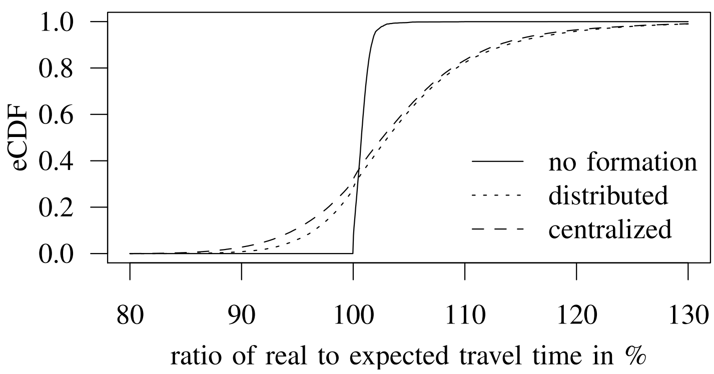

Figure 4.12 – eCDF showing the ratio of expected to real travel time per a car. A value smaller than 100 % means that the car reaches its destination faster than expected, a value greater than 100 % means that the car is slower.

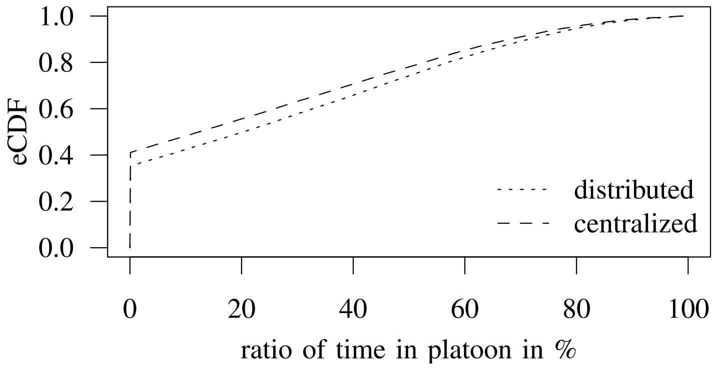

Figure 4.13 – eCDF showing the platoon time ratio per car

approach. Here, platoons are longer and cars stay in the platoon for a longer time, as they travel with slower speeds. On average, 28 % of the time is spent in a platoon in the distributed case compared to 24 % in the centralized case.

4.2.7 Fuel Consumption

Since a major benefit of platooning is the reduced air drag due to the small gap between cars, and, thus, a lower fuel consumption, we consider this effect in our study as well. The consumption depends on the speed and also on the distance to a preceding car, since this has an influence on the air drag. In order to simulate this effect, we added a model to Plexe to calculate the fuel consumption dependent on the reduced air drag due to the small gap.

Sovran [63] define a correlation between the change of the fuel consumption $\tilde{g}$ and the change of the air drag C_D by using a factor η:

$$\frac{\Delta \tilde{g}}{\tilde{g}} = \eta \cdot \frac{\Delta C_D}{C_D} \ , \tag{4.2}$$

where

$$\Delta \tilde{g} = \tilde{g} - \tilde{g}_{\text{platoon}} \ . \tag{4.3}$$

In order to simplify Equation (4.2), we define $\delta = \frac{\Delta C_D}{C_D}$, so that the fuel consumption $\tilde{g}_{\text{platoon}}$ for a car in a platoon can be modeled as

$$\tilde{g}_{\text{platoon}} = (1 - \eta \cdot \delta) \cdot \tilde{g} \ . \tag{4.4}$$

Cappiello et al. [100] derive a model to calculate the fuel consumption of a car from measurements and model fitting. Thus, we define the normal fuel consumption for a car not in a platoon $\tilde{g}$ as

$$\tilde{g} = \tilde{g}_{\text{Cappiello}} \ . \tag{4.5}$$

We use the following values for δ from Bruneau et al. [65], Table 5: $\delta_{\text{Lead}} = 0.12$, $\delta_{\text{Middle}} = 0.27$, and $\delta_{\text{Last}} = 0.23$.

Using Equations (4.4) and (4.5), $\eta = 0.46$ [63], and the values for δ, the fuel consumption of a car in a platoon $\tilde{g}_{\text{platoon}}$ can be calculated as

$$\tilde{g}_{\text{platoon}} = (1 - \eta_{\text{Sovran}} \cdot \delta_{\text{Bruneau}}) \cdot \tilde{g}_{\text{Cappiello}} \,, \tag{4.6}$$

where δ_{Lead} is used for the leading car, δ_{Last} for the last car, and δ_{Middle} for every other car in the platoon.

The resulting fuel consumption is plotted in Figure 4.14. The values plotted represent the total fuel consumption of cars until reaching the destination. The absolute values might be partially misleading as the model gives negative values when the deceleration is too high; it assumes that values are capped by different thresholds [101]. The qualitative effects, however, are correct and we can thus study the relation of the two platoon formation approaches.

As expected, platooning indeed helps saving fuel compared to the baseline. However, the distributed solution outperforms the centralized approach. Here, even though not the optimal platoons may be formed, overall, there are more cars in platoons and for a longer time. Also, the driving speed is slower in the distributed approach. Both aspects help reducing the fuel consumption.

4.3 Discussion

Comparing both approaches presented, we see that the centralized approach has more knowledge. It is aware of more vehicles and, thus, more candidates. However, many vehicles are filtered due to knowledge of their maneuver status. This has the advantage of fewer aborted join maneuvers. The distributed approach, however, does not know the maneuver status of the candidates, thus, producing needlessly

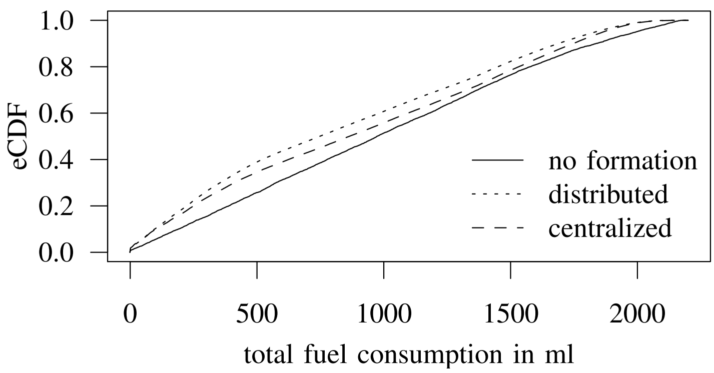

Figure 4.14 – eCDF showing the total fuel consumption per car

attempted maneuvers, which then are declined. On the other hand, the shown data evidences that being greedy (i.e., trying to keep joining the same candidates) eventually pays off. The distributed solution leads to longer platoons, as several cars eventually join the same platoon.

Both approaches need some time to find a platoon, however, the distributed solution is slightly worse. Additionally, it leads to more negative speed deviation and the deviation is larger in general (as platoons are longer and more cars need to adjust the speed to the same leader). When considering speed deviation combined with platoon size, i.e., the happiness, the distributed approach leads to happier cars, as longer platoons enable more cars to utilize the potential platooning benefits.

The slower driving speed of vehicles leads to a somewhat longer travel time in the distributed approach. Additionally, slow speed combined with longer platoons leads to more fuel savings in the distributed approach. In general, fuel savings can be acknowledged for both platooning approaches. Certainly, more time in a platoon also leads to higher savings, making the distributed approach the most beneficial regarding this metric.

Chapter 5

Conclusion

In this thesis, we investigate platoon formation as an optimization problem from the perspective of cars searching to join platoons. We develop both a centralized and a distributed approach using greedy heuristics to solve this optimization problem. We simulate both approaches and compare them using several (often used) metrics for platooning.

Our investigations show that the selection of formation algorithms is important, as it heavily influences the platoon assignments. Having more knowledge at hand can be beneficial in some ways but does not necessarily produce better (i.e., longer) platoons. The actual formation strategy as well as the individual capabilities of cars and drivers also have a huge impact on the result. Our simulations show that the willingness to compromise can pay off as more cars are able to benefit from platooning. Also, regarding often used metrics such as fuel consumption and travel time, the distributed approach appears to be more beneficial, even though its busy waiting approach is not very smart.

In future work, we plan to use more sophisticated join maneuvers (e.g., in the middle of a platoon and joining entire platoons) as well platoon splitting to support different trips. Also, we need to consider smarter approaches for the distributed solution compared to the busy wait whenever a join failed, potentially reducing the time find a platoon. Moreover, we plan to extend our optimization problem by incorporating more (individual) properties of cars such as mobility capabilities and a car's destination. Using these improvements and extensions, we aim to tackle the problem of platoon assignments with more advanced and more realistic models to make it applicable for use in future prototypes.

List of Abbreviations

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System
AHS	Advanced Highway System
BSS	Basic Service Set, *An AP in IEEE 802.11 wireless LAN provides a basic service set, which contains all associated nodes*
CACC	Cooperative Adaptive Cruise Control
CAM	Cooperative Awareness Message
CC	Cruise Control
CCH	Control Channel
CF	Car Following
CSMA	Carrier Sensing Multiple Access
CSMA/CA	CSMA with Collision Avoidance
DSRC	Distributed Short-Range Communication
FSM	Finite State Machine
HDV	Heavy Duty Vehicle
ICA	Intersection Collision-Avoidance
IDM	Intelligent Driver Model
ITL	Intelligent Traffic Light
ITS	Intelligent Transportation System
IVC	Inter-Vehicle Communication
LC	Lane Change
LTE	Long-Term Evolution
OCB	Outside the Context of a BSS
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection
PI	Proportional Integral
RF	Radio Frequency
RSU	Roadside Unit
RVC	Roadside-to-Vehicle Communication
SCH	Service Channel

TDMA	Time Division Multiple Access
V-VLC	Vehicular VLC
VANET	Vehicular Ad Hoc Network
VLC	Visible Light Communication

List of Algorithms

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