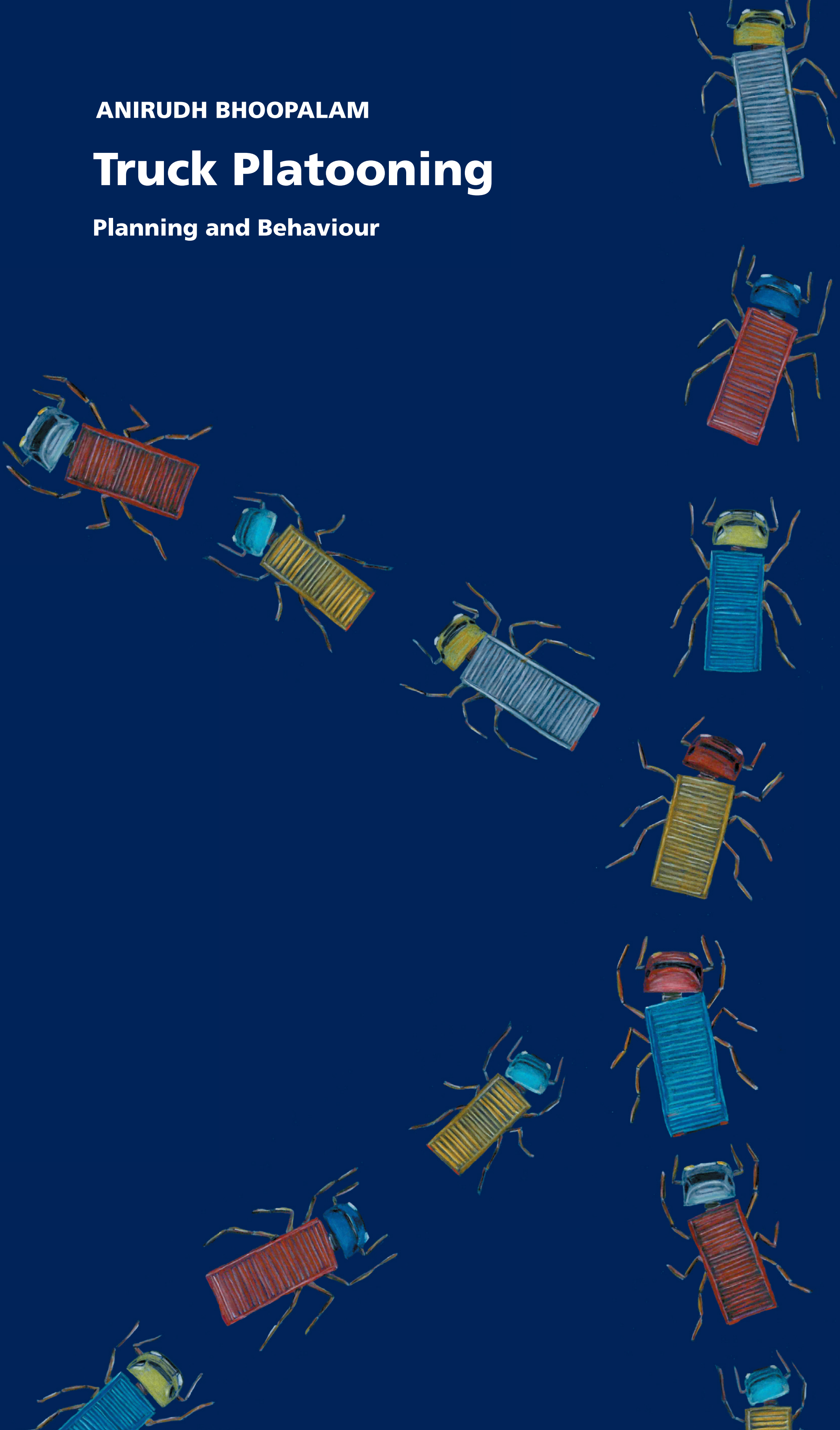
ANIRUDH BHOOPALAM

Truck Platooning

Planning and Behaviour



TRUCK PLATOONING

PLANNING AND BEHAVIOUR

Truck Platooning - Planning and Behaviour

Truck Platooning - Planning en Gedrag

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Erasmus University Rotterdam

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Many say doing a PhD can be lonely; luckily, mine was not thanks to my supervisors - Rob Zuidwijk and Niels Agatz. Both of them deeply cared not only about my work but also my general well-being, which is more than anything I could have ever hoped for. Rob, thank you for always finding time for me. Your enthusiasm for our work was contagious and kept me motivated to do well. Furthermore, as someone that had crippling stage fright growing up, I highly appreciated your guidance during my first teaching task. Niels, I genuinely could not have wished for a better daily supervisor. I could come to you with anything - work related and otherwise - and you always helped me out. Thank you so much for everything - from the engaging research discussions, to the dinners, to the poker nights, and for being a good friend. I am glad we both share an appreciation for "clean" pieces of text (and Ali G), which led to some intriguing conversations sometimes at 10pm on a Sunday night. Rob and Niels, I strongly hope we get to work together again.

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To conclude, I would like to refer to this one conversation I had with Kaveh and Joydeep at Paviljoen about whether spending the prime years of my 20s doing a PhD at RSM was the right choice. Yes.

Anirudh Bhoopalam
Rotterdam, 2021

P.S I wish I knew more ways to say ‘thanks’

Contents

1 Introduction

With the ongoing rapid developments in automotive technologies, a reality with autonomous vehicles is fast approaching. In fact, a few commercially available cars already offer advanced features like autopilot (Tesla, 2021), while several semi-autonomous features such as cruise control, parking assist, and lane-keeping assist have become commonplace. CB Insights (2020) reports the progress of over forty companies conducting research and carrying out tests with autonomous vehicles.

This heightened interest may be attributed to the benefits that autonomous vehicle technology offers. By eliminating human error and inconsistencies, it is likely that autonomous vehicles will improve safety and alleviate congestion (Gruel & Stanford, 2016). They allow groups such as the aged and physically challenged to independently use cars, thereby potentially increasing "equality in mobility". Furthermore, they free up time for commuters to carry out additional tasks (Pudāne et al., 2019). Apart from such direct benefits, autonomous vehicles could challenge some of society's traditional ways of operation. For instance, self-driving cars could work on a sharing model and operate as "driverless taxis", eliminating the need for car ownership (Combs, 2019; Masoud & Jayakrishnan, 2016). Such a system would reduce the total number of cars, which in turn, opens up space in central urban areas by not requiring parking spaces. Milakis et al. (2017); Gruel & Stanford (2016) outline such ripple effects of self-driving vehicles. Unsurprisingly, Brynjolfsson & McAfee (2014) often refer to autonomous vehicles as an important element of what they call the "second machine age".

With autonomous vehicles potentially being paradigm-shifting, a gradual and phased deployment is likely. An oft mentioned early application area is freight transport, more specifically, commercial trucking for a couple of reasons. First, autonomous vehicle technology has been successfully implemented in closed settings like warehouses or container terminals (Azadeh et al., 2019; Roodenbergen & Vis, 2001; Kim & Bae, 2004). Second, they reduce operating costs and increase hours of service leading to direct business savings for commercial fleet operators (Fritschy & Spinler, 2019). Companies have therefore begun developing and testing self-driving trucks (Hirsch et al., 2020; Frangoul, 2019; Tesla, 2019; Benz, 2015).

Despite the large investments, it is unlikely that autonomous trucks will be allowed on the road soon. Issues pertaining to safety, security, privacy, and liability still remain (Simpson et al., 2019; Fagnant & Kockelman, 2015). Consequently, legal and policy issues continue to exist (Slowik & Sharpe, 2018). Therefore, driver supervision would likely still be needed in the near future with further technological progress and testing would gradually reduce this requirement. With cruise control and lane-keeping assist commercially available, further progress in technology points to platooning as the next step. To ensure a smooth transition towards an autonomous vehicle future, it is crucial that platooning be implemented and managed well.

1.1 Truck platooning

A truck platoon is a set of virtually connected trucks that drive behind one another at short headways using automated driving technology. The leading truck or the *leader* is manually driven and followed by one or more following trucks or *followers*. The followers automatically brake, steer and (de)accelerate based on the actions of the leading truck. With time and progressing technology, we may see platoons with drivers resting while being in the truck or even platoons in which not all trucks require drivers, thereby moving closer and closer to a society with fully autonomous self-driving vehicles (Kilcarr, 2016). Figure 1.1 depicts a simple platoon.

Platooning offers a variety of benefits. Since the followers drive closely behind the leader, they experience less air resistance. As a result, they consume less fuel with savings estimated to be between four and thirteen percent (McAuliffe et al., 2018; Alam et al., 2015; Lammert et al., 2014). Not only is this beneficial for truck operators but also for the environment as it lowers emissions (Scora & Barth, 2006). In addition, platooning can improve traffic safety by reducing the risk of rear-end collisions. It also helps alleviate traffic congestion and increase throughput since trucks in a platoon occupy less space compared to when they drive separately (Lioris et al., 2017; Schladover et al., 2015; Van Arem et al., 2006). It is therefore no surprise that companies across the world have paid significant attention to platooning by conducting real-life tests - see, for example, Ministry of Transport - Singapore (2017); Eckhardt et al. (2016); Peloton Technology (2016); UNSW Engineering (2016); Tsugawa (2014).

Simultaneously, academic literature on truck platooning has also been growing. Early research efforts were mostly focused on technology issues (see Maiti et al. (2017); Bergenhem et al. (2012a) for overviews of different projects). Subsequent research began looking at a variety of such as the maneuvering of platoons in traffic (Calvert et al., 2019; Yang et al.,

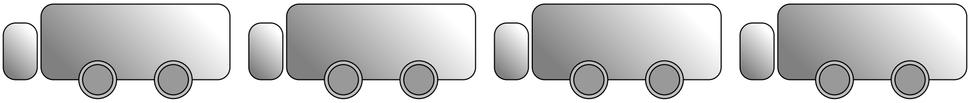

Figure 1.1: A truck platoon

2019), human factors/behaviour (Castritius et al., 2020b,a; Hjamdähl et al., 2017), policy implications (Bridgelall et al., 2020; Bao et al., 2018), planning (Bhoopalam et al., 2018; Larsson et al., 2015), effects on infrastructure (Steelman et al., 2021), interaction with other transport modes (Xue et al., 2021; You et al., 2020), and so on. All of these research directions were amongst the "open questions" identified in the European Truck Platooning Challenge (Eckhardt et al., 2016). This growing body of research is a clear indication of the concerted efforts towards making truck platooning, and therefore autonomous driving, a reality.

In this research, we contribute toward this endeavor by answering some remaining platooning questions in two domains - planning and behaviour. We explain these briefly before going into our specific research objectives and methods.

1.1.1 Planning

When platooning technology is commonplace, trucks may be able to spontaneously form platoons without any advance planning. However, when the deployment of platooning technology is not widespread or on routes with little freight traffic, careful centralized planning is required. This is especially important to be able to reap the benefits of platooning. Moreover, maximizing the benefits of platooning is in the general interest of the progress of autonomous driving technology.

To form a platoon, one needs to determine the departure times, speeds, and routes of the trucks. By extension, this would involve establishing where a platoon begins and ends. A truck may have to wait at a certain point or make a detour to be able to join a platoon. Figure 1.2 shows an example of a platoon with two trucks in which one truck makes a detour from its shortest path.

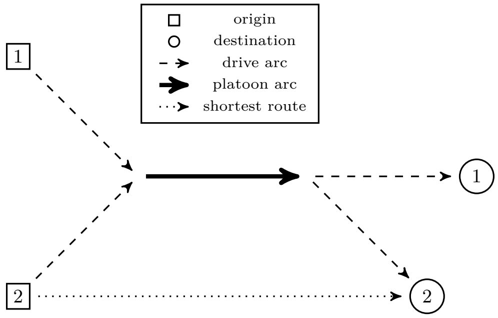

Figure 1.2: A two-truck platoon

With more trucks, the problem of determining and synchronizing their routes and time-schedules of each becomes complicated especially when trucks can join multiple platoons along their journeys. In such a case, the schedules and routes of trucks are more closely inter-dependent making the coordination of platoons more challenging. This illustrates that planning of platoons is not trivial and requires sophisticated decision support tools and models.

1.1.2 Behaviour

Alongside various operational aspects of any new technology, it is crucial to look at how its users perceive them. After all, for any technology to be successful, it needs to be accepted by the people it affects. Therefore, there has been extensive research related to technology acceptance in settings like office automation (Marquié et al., 1994; Hardin, 1960a,b), sales (Buttle et al., 2006; Morgan & Links, 2001), healthcare (Ziefle & Valdez, 2017; Pino et al., 2015; Hu et al., 2015; Pai & l Huang, 2011; Wilkowska & Ziefle, 2011; Walter & Lopez, 2008), education (Park & Han, 2016; Al-Emran et al., 2018; Almaiah, 2018) to name a few.

With regards to platooning, the group that is most affected is that of truck drivers. With progress in technology, the system will gradually take over more and more tasks that are part of a driver's job. Truck drivers' acceptance of these developments is important not only for the future of platooning but for that of automated driving in general. An implementation of this technology without considering driver views could leave them feeling disgruntled (Brown et al., 2002), slowing down the adaptation of automated driving in the process. Hence, it is critical acceptance of platooning by truck drivers be studied.

1.2 Research objectives and methodology

In this dissertation, we consider three research objectives, two corresponding to the planning perspective and one to the behavioural. The **planning** research objectives are -

P1. To identify and characterize different planning challenges that occur while creating and organizing truck platoons. This includes challenges that arise with progress in platooning technology where we may see platoons with trucks in which drivers may rest or platoons in which not all trucks may require drivers.

P2. To assist in strategic and operational decision making by building new and efficient quantitative tools to maximize platooning benefits.

For Objective P1, we thoroughly review the literature. We identify and link characteristics of platoon planning problems to existing and more well-established operations research models in the literature.

For Objective P2, we use our literature review as inspiration and draw inspiration from operations research models. The planning problems we consider share similarities with the multi-commodity flow problem and the strategic network design problem. Therefore, we use standard methods such as Integer and Stochastic Programming to formulate and solve them. Furthermore, we build heuristics based on graph theory and analytical geometry to solve larger instances of these problems. We test the performance of our methods on instances that represent real world cases.

Now, we state the **behavioural** research objective -

B1. To review the perceived benefits and hurdles of implementing platooning from a truck driver perspective. This again includes advanced forms where we may see platoons in which drivers may rest or platoons in which not all trucks may require drivers.

Objective B1 is exploratory, for which we use qualitative methods - interviews and focus groups. We interview experts to design our focus groups, which we then carry out with truck drivers. We use content analysis to extract insights from the focus groups data.

1.3 Contribution and thesis outline

This thesis contains six chapters. Chapter 1 introduces and motivates our research. Chapters 2-4 look at platooning from the planning perspective and aim to fulfill research objectives P1 and P2, while Chapter 5 deals with the behavioural research objective B1. Finally, Chapter 6 explains our conclusions and recommendations for future research. The specific research questions and contributions per chapter are as follows -

Chapter 2: Planning of truck platoons: A literature review and directions for future research[1]

This chapter identifies and classifies the different planning problems that arise in truck platooning, reviews the emerging literature related to this planning, and points towards directions for future research. We formulate the following research questions -

- What are relevant planning problems to support platooning?
- What are relevant operations research models and approaches for these problems in the literature?
- What are the gaps and areas for future platoon planning research?

We specify different possible objectives and constraints for platoon planning, which allows us to compare it with other collaborative transport systems such as ride-sharing and freight consolidation. We also look at platooning under different dynamics - ranging from scheduled platooning where everything is known and planned in advance; to opportunistic platoon

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[1] Bhoopalam, A. K., Agatz, N., & Zuidwijk, R. (2018). Planning of truck platoons: A literature review and directions for future research. *Transportation Research Part B: Methodological, 107*, 212-228

where trucks form platoons they encounter on the road. When the deployment of platooning technology is not widespread, opportunistic platooning will not be very successful in creating platoons and therefore some form of planning is required (Liang et al., 2014). We then classify the platooning literature on two frameworks - (1) flexibility in routing and presence of restrictions on platoon size; (2) level of involvement of human drivers in a truck in a platoon. While doing so, we link each of these settings to existing operations research models and thereby provide an outlook for the unexplored settings. Following this, we discuss how platooning might affect traditional vehicle routing and network design settings. Finally, we identify four areas for future research in platooning - (1) optimization and development of heuristics; (2) dealing with uncertainty; (3) system sustainability to ensure long-term success; and (4) network design.

Chapter 3: Spatial and temporal synchronization of truck platoons [2]

This chapter builds algorithms to route trucks in platoons with a specific focus on finding fast solution methods for problem settings in which two trucks platoon together and all trucks are in at most one platoon per trip. We aim to answer the following research questions -

- How can the routes and time schedules of two-truck platoons be efficiently determined?
- What are the advantages and disadvantages of restricting the number of platoons trucks can join on their journeys?
- What are the advantages and disadvantages of restricting the number of trucks per platoon?

To answer these research questions, we model and analyze different versions of the platooning problem. We define the *Platoon Routing Problem with Time Windows* (PRP-TW), which has no restrictions on the number of platoons a truck can be a part of in a journey or the number of platoons per trip. We formulate a MIP to compute a benchmark. To study the effects of the restrictions, we define special cases - the *Platoon Pair Routing Problem with Time Windows* (PPRP-TW) and the *Platoon Pair Routing Problem* (PPRP). To solve the PPRP-TW and the PPRP, we propose methods that establish an equivalence of these problems with the shortest path problem and show they are of polynomial complexity. Based on these methods, we build several fast heuristics to solve the PRP-TW.

By means of a computational study, we compare how these different models perform on a set of practically relevant instances representing the Netherlands. We observe that the heuristics perform well. Moreover, we see that simple two-truck platoons capture most of the potential savings of platooning.

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[2] Bhoopalam, A. K., Agatz, N., & Zuidwijk, R. (2020). Spatial and temporal synchronization of truck platoons. *Under review, Available at SSRN*: `http://dx.doi.org/10.2139/ssrn.3741234`

Chapter 4: Scenario-based Platoon Lane Network Design [3]

Having dedicated lanes for truck platooning has several advantages. By separating platoons from regular traffic, one can ensure they stay in formation continuously without interference. Furthermore, as trucks contribute to the wear and tear of road infrastructure, giving platoons their own lane would prolong the life of roads where regular traffic operates. As a result, the emissions from trucks would go down. In this chapter, we build methods to determine which parts of an existing network are most suitable to add platooning lanes to. In particular, our research questions are -

- Given a budget, to which parts of a network should dedicated platooning lanes be added to such that emissions are minimized?
- What is the impact of uncertainty in demand distribution on the design of a network for platooning?
- What are the impacts of spatial and temporal constraints on platooning network design?

As indicated by the second research question, such strategic settings are subject to uncertainty. We define and formulate the *Platoon Lane Network Design Problem* (PLNDP), where we use scenarios to model uncertainty. Having a large number of scenarios would improve solution quality but increase computational effort. Therefore, we present methods to blend network designs obtained by solving PLNDP multiple times, each with few scenarios.

We assess the performance of our approaches by using computational experiments on practically relevant instances representing Germany. We observe that our combining methods generate good network designs, which perform well on test instances. These designs require significantly less computational effort compared to solving PLNDP with a large number of scenarios.

Chapter 5: The long road to automated trucking: Insights from driver focus groups [4]

With progressing technology, we may see advanced forms of platooning where drivers can rest while being in the truck, or platoons in which not all trucks require drivers. Therefore, platooning has a significant impact on the jobs of truck drivers. We consider the following research questions -

- What are the various perceptions of drivers on the different forms of truck platooning?
- What are driver perspectives regarding the advantages and disadvantages of the advanced forms of truck platooning for their jobs?

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[3] Bhoopalam, A. K„ Agatz, N., & Savelsbergh, M. (2021). Scenario-based Platoon Lane Network Design. *Available at SSRN*: `http://ssrn.com/abstract=3933988`

[4] Bhoopalam, A. K, van den Berg, R., Agatz, N., & Chorus, C. (2021). The long road to automated trucking: Insights from driver focus groups. *Under review, Available at SSRN*: `http://dx.doi.org/10.2139/ssrn.3779469`

In the literature, similar research exists for the most basic form of platooning where drivers are present and attentive in all trucks of a platoon (Castritius et al., 2020b; Yang et al., 2018). By looking at the advanced forms, we aim to open the pathway towards more concerted, quantitative, and confirmatory research efforts in the area and consequently contribute toward the implementation of automated driving. Given our exploratory goal, we conduct focus groups with truck drivers at different truck stops in the Netherlands. The drivers were allowed to freely express their thoughts with the moderator guiding the discussion and keeping all participants involved where we allowed.

These focus groups indicate that drivers foresee that platooning will eventually become a reality but believe it will have a negative impact on the quality of their work and their job satisfaction. They see platooning affecting the parts of the job they enjoy they most while reducing their autonomy and freedom.

Research Statement

This Ph.D. thesis has been written during the author's work at the Erasmus University Rotterdam. The author is responsible for formulating the research questions, building the analytical models, analyzing the results, and writing all the chapters of this thesis. While carrying out the research, the author received valuable and constructive feedback from the doctoral advisors and other doctoral committee members, which subsequently increased the quality of research.

2 Planning of truck platoons: A literature review and directions for future research

2.1 Introduction

Novel semi-automated driving technologies, collectively referred to as Cooperative Adaptive Cruise Control (CACC), enable trucks to drive very close together as a platoon. Trucks in a platoon are virtually linked and communicate with each other through wireless communication technology. The leading truck is manually driven at the first position of the platoon and automatically followed by one or more following trucks. This means that the following trucks automatically brake, steer and (de)accelerate based on the actions of the leading truck.

Truck platooning has been the subject of heightened interest recently because of the different benefits it provides, both for individual truck operators and society. Driving close together reduces fuel consumption as it improves the aerodynamics of all trucks in the platoon (Patten et al., 2012; Zabat et al., 1995). Test track experiments suggest savings of up to six percent for the leading truck and ten percent for the following trucks (Alam et al., 2015; Lammert et al., 2014).

While less fuel consumption leads to costs savings for the truck operators, it also reduces emissions (Scora & Barth, 2006). This is relevant as heavy-duty road transport is responsible for a large part of all traffic emissions (European Commission, 2016). Furthermore, platooning can enhance traffic safety by providing significantly lower reaction times and less room for human error within the platoon, which can reduce the number of rear-end collisions. Also, trucks in a platoon take up less road space than when driving separately, which may reduce traffic congestion (Schladover et al., 2015; Van Arem et al., 2006) and therefore, increases traffic throughput (Lioris et al., 2017).

Automated driving has been successfully deployed in closed environments in various logistics and freight transportation settings such as port terminals (Kim & Bae, 2004) and warehouses and factories (Azadeh et al., 2017; Roodenbergen & Vis, 2001). Truck platooning can be considered as a first step towards automated freight transportation in an open and uncontrolled environment. Given the development of automated driving technology, we expect that the following trucks in a platoon would not require drivers in the future (Kilcarr, 2016).

All major truck manufacturers have developed technologies that allow platooning, and several field tests are planned or are currently taking place in Europe (Eckhardt et al., 2016), the U.S. (Peloton Technology, 2016), Singapore (Ministry of Transport - Singapore, 2017), Japan (Tsugawa, 2014) and Australia (UNSW Engineering, 2016). The first road-legal trucks equipped with platooning technology are expected soon.

When a sufficient number of vehicles are capable of platooning, it is likely that platoons can be spontaneously formed without planning in advance. However, in the initial stages, when the deployment of platooning technology is not widespread or on routes with little freight traffic, careful centralized planning is required to create platoons (Janssen et al., 2015). A so-called platooning service provider (Roland Berger, 2016; Janssen et al., 2015) could bring together trucks from different fleets in a platoon. Platoons can be scheduled in advance or planned in real-time during execution.

To establish a platoon, the departure times, travel speeds and the routes of the trucks in the platoon must be synchronized. A truck may, for instance, adjust its route and possibly even make a small detour to join a platoon. Figure 2.1 depicts an example of a platoon between two trucks in which one of the trucks makes a detour to form the platoon.

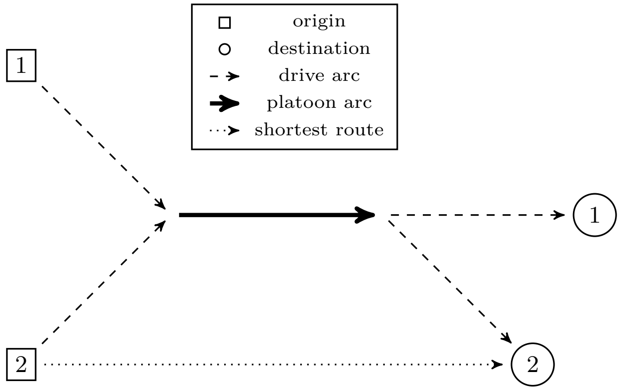


Figure 2.1: A two-truck platoon

Complex planning problems may arise in creating platoons, especially when considering detours. To fully reap the benefits of truck platooning, now and in the future, sophisticated decision support models and tools are required. Such models are not only useful to support platooning operations but can also help quantify the potential benefits of different types of platooning. While there has been much attention for the technological issues (see Bergenhem et al. (2012b) for an overview of recent projects), safe manoeuvring of platoons (see Kavathekar & Chen (2011) for an overview), human factors (for example, Heikoop et al. (2017); Hjamdähl et al. (2017); Yamabe et al. (2012); Larburu et al. (2010)), we are not aware of a paper that systematically reviews the challenges of platooning from a planning and transportation optimization perspective.

This chapter aims to fill the above mentioned gap by classifying the different planning problems that arise in truck platooning, reviewing the emerging literature related to this planning and identifying directions for future research. More specifically, the goal of this paper is fourfold: (1) provide a systematic overview of different forms of platooning; (2) identify and define relevant planning problems to support the different forms of platooning; (3) provide an overview of relevant operations research models and approaches for these problems in the literature and; (4) identify gaps and areas for future research.

This chapter focuses on truck platooning but similar issues may arise in the planning of platoons of regular cars and other vehicles not only on the road but also on water (see Lauf (2017); TU Delft 3mE (2017)) and in air (see Chen et al. (2015); Richert & Cortés (2012)).

The chapter is structured as follows. Section 2.2 explains the main characteristics of platooning planning. In Section 2.3, we compare platooning with other collaborative transport systems such as ride-sharing and freight consolidation. Section 2.4 describes different platoon settings and related static planning problems from the literature. Section 2.5 discusses planning problems that arise when technology and legislation allow platoons with (partially) driverless trucks. Section 2.6 discusses the planning of platoons in real-time. Section 2.7 looks at vehicle routing with platooning. The effects of platooning on network design are discussed in Section 2.8. Finally, Section 2.9 identifies some future research opportunities and concludes the chapter.

2.2 Characteristics of truck platoon planning

This section discusses several important characteristics of platoon planning. First, we discuss the planning process and the planning dynamics. Then, we present possible planning objectives and constraints. We conclude this section with a discussion on the issues related to dividing the benefits of platooning among the different participants.

2.2.1 Platoon planning process and dynamics

To explain the planning processes, we consider a platooning service provider that creates platoon plans based on the trip information from different trucks. Each trip announcement specifies an origin location, a destination location, an earliest departure time, and a latest arrival time at the destination. We assume that there is typically some flexibility in the departure time, i.e, it is not necessary to leave at the earliest departure time to arrive at the destination before the latest arrival time. Moreover, there may be different possible routes between the origin and the destination. The trip announcement also specifies the characteristics of the truck and its load and could contain preferences for the position within the platoon.

A platoon plan specifies (1) which trucks platoon together, (2) where and when the trucks form a platoon, (3) the route the platoon will take and (4) in what sequence the trucks drive within the platoon. Based on these platoon plans, the different trucks then typically form platoons en-route. For more information about the en-route formation of a platoon while interacting with surrounding traffic, see e.g., Segata et al. (2014); Bergenhem et al. (2012b). Trucks can wait for one another to form a platoon or can catch up by adjusting their driving speeds. To catch up, the truck that is behind can speed up or the truck that is in front can slow down. However, due to speed limits, forming platoons in this way is likely to require too much time in most practical settings.

Depending on when the trip announcements become available, we can distinguish the following three situations.

Scheduled platoon planning. All trips are announced before the start of the operations. Therefore, all platoon plans can be created in advance. This is often referred to as off-line or static planning.

Real-time platooning. Truck operators announce their trips closely before departure or even when the trucks are en-route. Therefore, trip announcements arrive during the execution of the trips. This is often referred to as online or dynamic planning.

Opportunistic platooning. Trucks that are in close proximity of each other form platoons dynamically on the road without any prior planning. This type of platooning is also referred to as spontaneous, ad-hoc or on-the-fly platooning (Janssen et al., 2015; Liang et al., 2014).

When the deployment of platooning technology is not widespread, opportunistic platooning will not be very successful in creating platoons and therefore some form of planning is required. A simulation study by Liang et al. (2014) shows that there are substantial benefits associated with the careful planning of platoons. In the subsequent sections of the chapter, we first discuss various aspects of scheduled platoon planning and then highlight the additional challenges in real-time platoon planning.

2.2.2 Platooning objectives

To create platoons, a platooning service provider can consider different objectives. Here, we discuss two important ones.

Minimize the system-wide fuel cost

This objective aims to minimize the total fuel cost of all trucks in the system. To determine the net costs of a platoon, one should not only consider the fuel savings that occur within the platoon but also the additional fuel consumed to create the platoon due to detours or speed changes. The minimization of the fuel costs would initially be one of the main operational benefit of platooning for individual truck operators.

By minimizing the fuel costs, we also implicitly increase some of the societal benefits of platooning. Minimizing fuel consumption is equivalent to minimizing emissions (Scora & Barth, 2006). Also, when we minimize the fuel costs, longer platoons are preferred as the total savings will be higher with more following trucks in the system. Such longer platoons are associated with more efficient road utilization since the trucks within a platoon drive closer together.

Note that minimizing fuel costs does not necessarily reduce traffic congestion as it may increase the number of trucks on a specific road segment. On the one hand, the reduced space utilization as a result of platooning might help improve the traffic throughput. On the other hand, when too many trucks take the same route at the same time in an effort to form platoons, they may create traffic congestion.

Maximize the number of trucks in a platoon

Instead of minimizing the system-wide fuel cost, a platoon service provider could also maximize the number of matched trucks in the system. The increased likelihood of finding a platoon may be an important criterion to keep truck companies involved. Furthermore, involving more companies by creating more matches in the initial stages of technology deployment could help spread confidence and trust in the system. The higher matching rate could consequently stimulate larger participant pools by attracting more truck companies in the future. Moreover, the possibly higher number of platoons created as a result of this objective may help gain more experience with automatic driving and platooning which could prove to be invaluable for the future success of the system. Note that this objective could potentially not be completely aligned with the previously described objective of minimizing the fuel costs.

2.2.3 Constraints on platoon formation

Various prerequisites determine whether it is feasible to form a platoon between a set of trucks. One of the most important constraints is the timing of the trips. Since freight transportation typically operates within tight time windows that are specified by the customers, there may be only little flexibility to wait for another truck to form a platoon. Instead of hard constraints on the time windows, table 2.1 shows that some studies consider soft time constraints by penalizing delays.

Besides the customer imposed time windows, platoons also have to abide by driving time regulations (Goel, 2014; Goel et al., 2012; Goel & Rousseau, 2012; Goel, 2010). These regulations dictate specific time periods in which trucks need to take breaks. Incompatible break times may render certain platoons infeasible.

Furthermore, it may not be possible to form platoons between certain types of trucks. The platooning technologies of different truck manufacturers are currently incompatible, so it is only possible to form platoons with trucks of the same brand (Brizzolara & Toth, 2016; Berger, 2016). Also, the nature of the load (for example, dangerous goods) may preclude a truck from being part of a platoon (Meisen et al., 2008).

It is likely that there will be legal limitations on the number of trucks in a platoon (Eckhardt et al., 2016). This is to prevent long platoons disturbing the traffic flow by making it difficult for other vehicles to merge onto highways. Additionally, long platoons could lead to increased wear and tear of roads and bridges since such infrastructure has not been designed for dense truck platoons.

Also, the required communication technology for platooning may not be very reliable in tunnels. As a result, it may become necessary to construct dedicated infrastructure for platoon traffic. This type of routing constraints are considered in the area of convoy planning (see Tuson & Harrison (2005); Kumar & Narendran (2010); Tuson & Harrison (2005); Chardaire et al. (2005) for an example).

Apart from these technical and operational constraints, personal and inter-organizational considerations may also play an important role in platoon formation. That is, not all companies would be willing to platoon with each other because of concerns related to trust or competition. Due to these issues, some companies may only want to form platoons within their own fleets or within a restricted coalition of fleets.

Next to restrictions on which trucks can form platoons together, there may be restrictions on the platoon sequence. That is, loading weights, torque ratings and the brake capacity determine safe possible truck sequences in a platoon (TNO, 2016). For example, trucks should be arranged in ascending order of their engine power to mass ratio. This is to ensure that the leading trucks do not pull away on uphill terrain (Nowakowski et al., 2015). Safety is another important consideration. To prevent collisions, for example, the truck with the worst braking performance should drive in front.

Table 2.1 provides an overview of the different objectives, constraints, and the decision variables that are used in the platooning literature.

2.2.4 Dividing the benefits of platooning

Trucks that participate in a platoon directly benefit from lower fuel consumption. However, these savings depend on the position in the platoon as there are more savings for the following truck(s) than for the leading truck. Moreover, trucks may incur different costs, such as detour costs, to join the platoon. This means that it may be necessary to redistribute the total system-wide benefits among the different participants in a platoon. In determining the total benefits, one should not only consider the benefits within the platoon but also the costs associated with forming the platoon such as the detour and waiting costs.

With scheduled truck platoons, simple proportional rules may be an appropriate way to divide the total system-wide benefits. However, this becomes difficult in a dynamic setting in which trucks can join and leave a platoon at any time. This is related to the division of shared benefits in multi-passenger ride-sharing (Furuhata et al., 2013). The issue is related to the stream of literature on inter-organizational collaboration (Cruijssen et al., 2007). Much of the research in this area makes use of cooperative game theory which considers scenarios where different parties form alliances that aim to achieve some goals jointly in an attempt to increase their individual profits (see Elkind & Rothe (2016) for more information). Cooperative game theory has been extensively applied to solve various benefit allocation problems in the area of logistics. For examples of applications, see Lozano et al. (2013); Frisk et al. (2010); Krajewska et al. (2008) and for a review of studies, see Guajardo & Rönnqvist (2016).

If the same trucks regularly platoon together as in a coalition, they could share the benefits by taking turns as leading truck. Richert & Cortés (2012) propose a similar idea in the context of unmanned aerial vehicles (UAVs). This is also comparable to carpool schemes in which different participants act as driver each time, e.g., Fagin & Williams (1983) propose scheduling algorithms to determine which carpool participant should drive in each carpool to fairly divide the workload. Likewise, one could assign the more beneficial following positions to the truck that incurs most costs to join the platoon.

Another consideration in the centralized planning of platoons is that system-optimal solutions are not necessarily optimal for each of the individual participants. A solution is not 'stable' if there exist pairs of trucks that are better off forming a platoon together than with the system assigned platoon partners. Wang et al. (2017) study this concept in the context of dynamic ride-sharing.

It may also be difficult to establish system-optimal solutions due to strategic behaviour of the participants. To maximize their own benefits, truck operators may reveal false information if it means they find a better match.

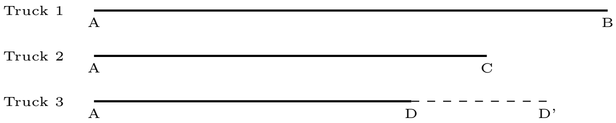


Figure 2.2: Example of strategic behaviour by truck 3

Table 2.1: Overview of platoon planning literature

Author(Year)	**Objective**		**Constraints**				**Decisions**				**Dynamics**		
	Fuel	Delays	Timing	Speed^1	Detour	Length	PC	R	S	SC	Scheduled	Real-time	Opportunistic
Sokolov et al. (2017)	•		•		•		•	•	•		•		•
Zhang et al. (2017)	•	•	•				•		•		•		
Adler et al. (2016)	•	•	•			•	•					•	
Larson et al. (2016)	•		•		•		•	•	•		•		
Liang et al. (2016)	•		•	•			•			•		•	
Van de Hoef (2016)	•		•	•			•		•	•	•	•	
Nourmohammadzadeh & Hartmann (2016a)	•		•				•	•	•		•		
Larsson et al. (2015)	•		•				•	•	•		•		
Liang et al. (2014)	•		•	•			•		•	•	•		•
Liang et al. (2013)	•			•	•		•			•		•	
Larson et al. (2013)	•		•	•			•	•		•	•	•	
Meisen et al. (2008)	•	•	•			•	•				•		

PC - platoon composition, R - route, S - schedule, SC - speed changes
1 - studies without a speed constraint assume a fixed driving speed

A simple example is shown in figure 2.2. Here, three trucks need to travel from A to B, C, and D respectively. The system-optimal solution would entail a platoon with trucks 1 and 2 since the overlap in their routes is the largest. Knowing this, truck 3 could falsely report his destination as D' resulting in a platoon with trucks 1 and 3. Clearly, this isn't the system-optimal solution any more as truck 3 would leave the platoon.

To prevent strategic behaviour, one may use formal agreements or contracts (see for example Schwartz & Scott (2003)). Another way is to create a collaboration mechanism that ensures all the parties act in a way that contributes to system efficiency (Xu, 2013). This is linked to the area of strategy proofness and mechanism design (see Nobel Prize Committee (2007); Parks (2001)). Strategic behaviour could also be prevented by using a reputation system (see Resnick & Zeckhauser (2015); Gupta et al. (2003) for examples and Mui et al. (2002) for an overview) which also incorporates factors such as company and driver trust. These systems could also discourage non-compliance from the truck operators.

2.3 Comparison with other collaborative transportation systems

Platooning entails the collaboration between multiple vehicles to increase the efficiency of the transportation system. As such, it shares some features with other forms of collaborative transportation. In this section, we highlight some of the key similarities and differences between platooning and freight consolidation and ride-sharing.

2.3.1 Freight consolidation

Freight consolidation is used as a means to facilitate more efficient and frequent shipping by combining large freight flows between terminals through a few links (Campbell, 1990). When multiple trucks with similar routes and time schedules have spare capacity, their loads may be combined. Therefore, freight consolidation requires the matching of trucks with the load they need to pick up and deliver. An overview of the various forms of consolidation and consolidation strategies can be found in Hall (1987).

Like platooning, freight consolidation is aimed at reducing travel costs and vehicle emissions. A key difference is that platooning does not involve the transfer of load between trucks which makes it more flexible than freight consolidation with respect to the compatibility of load. This means that full trucks could also form platoons. Moreover, trucks may form platoons anywhere in the network whereas freight can be consolidated only at certain dedicated facilities. Therefore, truck platooning requires less coordination between the different parties than in freight consolidation.

A platoon can be viewed as a *consolidation transport mode* (Crainic & Kim, 2007) that typically moves freight originating from different customers and destined for different locations. Platooning could prove to be a more economical alternative to freight consolidation since it does not require any additional infrastructure and is much more flexible. Therefore, platooning may be viewed as “on the fly” consolidation.

Min & Cooper (1990) provide an overview of different analytical studies looking at freight consolidation. They describe different solution methods used in the various studies. Most studies use heuristic and simulation approaches. A more recent review with a focus on the routing aspects is provided by Gansterer & Hartl (2017).

2.3.2 Ride-sharing

Ride-sharing is the practice of sharing rides as a means of reducing congestion, pollution and fuel costs by using empty seats of passenger cars. The rationale behind ride-sharing is akin to that of freight consolidation as discussed above. Similar to load being consolidated into fewer vehicles, people travel to their destinations in fewer vehicles. A difference with freight consolidation is that people are less flexible than load specially with respect to travel and waiting times.

Traditionally, ride-sharing or carpooling was used by people regularly travelling to the same place at the same time (Levofsky & Greenberg, 2001). In today’s world, ride-sharing systems exist that dynamically match riders with drivers, in real-time, based on their locations and times.

In ride-sharing, drivers are matched with riders that need to be picked up at their origins and dropped off at their destinations. Similar to freight consolidation, the pick up and drop off locations are fixed at the origin and destination. The service time is determined by the time it takes for this pick up and drop off to be executed.

Truck platooning and ride-sharing may result in less fuel consumption and consequently, reduced emissions. They involve matching entities with similar routes and time schedules.

Both of them operate under certain capacity constraints. For ride-sharing, the capacity is associated with the number of seats in the car. For platoons, the number of trucks in a platoon is conceptually unlimited but will likely be restricted by legislation. Also like in platooning, drivers part of ride-sharing services are likely to have to make some detours or adjust their time schedules to pick up riders.

Ride-sharing has recently started to receive much attention in literature. Furuhata et al. (2013) and Agatz et al. (2012) provide reviews of the different studies and the various solution methodologies in ride-sharing literature. Similar concepts have also been applied to freight (see Arslan et al. (2016)). Table 2.2 summarizes the comparison between platooning, ride-sharing and freight consolidation.

Table 2.2: Comparison of platooning with ride-sharing and freight consolidation

	Truck platooning	**Ride-sharing**	**Freight consolidation**
Supply			
Entity	Trucks	Drivers	Trucks
Capacity	Allowed maximum platoon size	Vehicle capacity (no of passengers)	Load weight and volume limits
Demand			
Entity	Trucks	Riders	Load
Location	Flexible	Fixed	Fixed
Service time	Negligible	Pick up and drop off time	Loading and unloading time
Service quality	Detour, excess travel time, success rate	Detour, excess travel time, success rate	Detour, safety, reliability
Benefits			
Individual	Reduced labour and fuel costs	Reduced costs due to shared capacity	Reduced costs due to economies of scale
Societal	Reduced emissions, road utilization	Reduced emissions, road utilization	Reduced emissions, road utilization

2.4 Scheduled platoon planning

In this section, we classify different platoon planning problems and discuss the relevant literature. Our classification is based on practical considerations that are likely to play an important role in planning platoons. We consider two characteristics to classify the platooning literature as described below.

Fixed vs. flexible routes To form good platoons, it may be beneficial for trucks to deviate from their individual shortest routes. However, in practice, certain operators might not be willing to alter their pre-planned routes to simplify planning. In such cases, the routes are fixed and therefore, routing is not part of the platoon planning decisions.

Restricted vs. unrestricted platooning As we discussed in section 2.2.3, there are likely to be restrictions on the number of trucks in a platoon in practice to restrict the impact on traffic and lessen the additional wear and tear on infrastructure. Furthermore, one may also want to minimize the number of platoons each truck is part of in a single trip to, for example, make the division of benefits simpler. Some examples of such restrictions are shown in figure 2.3.

Table 2.3 presents the platooning literature classified in this manner. We begin with a description of the unrestricted cases; then we introduce the different restrictions.

2.4.1 Unrestricted platooning

In the unrestricted setting, a truck may join and leave a platoon en route at any point in time. Moreover, there are no restrictions on the number of trucks in a platoon. A simple example of such a scenario with four trucks is depicted in figure 2.4.

2.4.1.1 Unrestricted platooning - fixed routes

The conceptual problem for this setting involves determining the departure times and/or speeds of different trucks as to maximize the overlap in their routes which would corre-

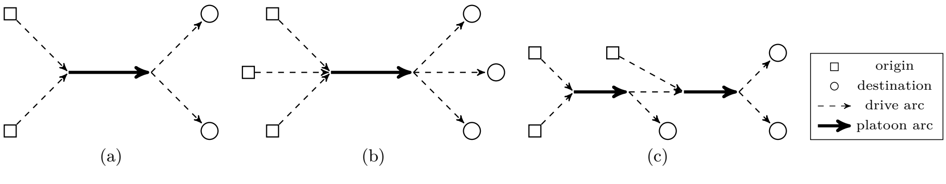

(a) (b) (c)

Figure 2.3: Examples of restricted platoon settings - (a) a two truck platoon - single platoon per trip, (b) a three truck platoon - single platoon per trip, and (c) a two truck platoon - multiple platoons per trip

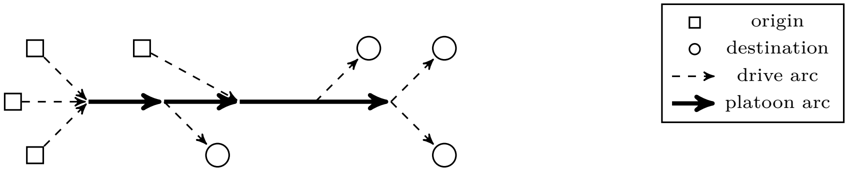


Figure 2.4: Unrestricted platooning - trucks allowed to join and leave a platoon at any instant

spond to a platoon. As driving in a platoon reduces fuel consumption, this objective would maximize the fuel savings from platooning.

Van de Hoef (2016) considers this problem for a large fleet of trucks. Using truck information, a centralized coordinator computes the vehicle plans for each truck which contain the routes and speed profiles so that they reach their destinations before the deadlines. A list of feasible platoon pairs is found taking into consideration the overlap in the routes and the time schedules. For each pair, they determine the optimal speed profile as to maximize overlap. These platoon pairs are then used as building blocks and merged to possibly form multi-truck platoons. The associated combinatorial optimization problem is shown to be NP hard and a local improvement heuristic for the fuel savings is presented to solve large problem instances. Then, the timings of platoon formation and split up are adjusted in a convex optimization problem to minimize fuel consumption. They test their approach with random transport assignments in mainland Sweden with up to 2000 trucks. They observe that the local improvement heuristic produces savings within thirty percent of the upper bound.

Liang et al. (2016) adjust the speeds for two trucks to form a platoon while also taking the deadlines into account. For multi-truck platoons, they propose a pairwise matching heuristic that is similar to the one presented in Larson et al. (2013) where each pair of trucks with fuel savings are fixed as one unit in the subsequent step of the heuristic and so on. To find the savings per pair of trucks, they use a fuel model which considers the speeds in addition to topographic and vehicle characteristics. In this study, they allow the lead vehicle to slow down in addition to the following vehicle speeding up to form platoons and conclude that it is more efficient.

Zhang et al. (2017) focus on the sub problem of determining feasibility of a pair of trucks by studying the platoon coordination problem under travel time uncertainty. As part of a cost minimization framework, they focus on determining the savings for a pair of trucks considering fuel related costs, travel-time related costs, and penalties for deviating from the planned schedule. When both trucks follow the same path, they observe that above a certain threshold in the waiting time, the vehicles are better off driving alone since the penalties outweigh the fuel savings. They extend their analysis to converging and diverging routes and find that platooning on converging routes is less beneficial due to the extra costs of waiting at the merging point on the network.

As we explained earlier in section 2.2.2, having too many trucks on the same road to maximize the platooning potential could cause congestion and be detrimental to the system. Using this line of reasoning, Farokhi & Johansson (2013, 2014) consider vehicles that decide their time of travel based on their preferred time, average traffic velocity and the congestion tax at that time. In this study, the authors consider a single stretch of road and therefore, the route is fixed. Trucks that can platoon have an additional incentive use the road at the same time as other trucks. They model the problem as a congestion game and use game theoretic concepts to study how the traffic flow and platooning incentives interact. One of their observations is that if there are more fuel savings associated with platooning, more trucks start travelling in similar time intervals.

2.4.1.2 Unrestricted platooning - flexible routes

In this setting, the platoon planning problem includes determining the routes of each truck in addition to the departure times and/or speeds. The additional routing decisions make the problem more difficult to solve. A number of studies in the literature consider this problem.

Larson et al. (2013) consider a simplified version of the problem in which local controllers placed at various street junctions carry out the optimization process by taking into account approaching trucks' speeds, positions and destinations. This means they only consider trucks that are close to each other which reduces the number of platoon possibilities. In a restricted version of the problem, they do not allow trucks to travel on a path where the travel time is longer than the shortest path travel time. This is to ensure that the vehicles reach their destinations on time. When platoons of more than three trucks are considered, the problem becomes intractable and so they propose a pairwise matching heuristic where platoons with the highest savings are fixed as one unit in the next step of the heuristic and so on. When they allow the trucks to deviate from their shortest time paths, the savings are slightly higher than when the routes are fixed. The authors test their local algorithm on instances involving up to 8000 vehicles on the German autobahn network.

Larsson et al. (2015) adopt a global perspective by considering all trucks in the system. They model this as a graph routing problem and prove that it is NP-hard. They also introduce a simpler version of the problem called the unlimited platooning problem where the deadlines are discarded. Like Larson et al. (2013), they propose a heuristic where they merge the pair of platoons with the highest savings. In addition to this best pair heuristic, they also present a hub heuristic where the problem is broken down into sub-problems. They split the trucks and select hubs for each subset. The problem is then to route the trucks from the origins to the hub and then to the destinations. The trucks are partitioned based on the edge ratings which represent the probability of a truck to drive over that edge. Then, they use a local search to further improve the results of both the heuristics. They test their approaches on instances on a graph representing the German autobahn network similar to the one used by Larson et al. (2013). For instances involving up to ten trucks, optimal solutions are generated within minutes and the heuristics produce near optimal solutions in most cases. They also consider a special case in which all the trucks have the same origin which they exactly solve for instances of up to 200 trucks. Here, the best pair heuristic with the local search produces near optimal solutions in most cases.

Larson et al. (2016) also adopt a system-wide perspective and formulate a mixed integer programming model with the objective of minimizing the amount of fuel used. The trucks are allowed to wait to form platoons. They perform experiments on a simple grid network and a representation of the Chicago highway network for instances with 25 trucks.

Nourmohammadzadeh & Hartmann (2016a) propose heuristics based on a genetic algorithm. In comparison with the optimal solutions for smaller instances of ten trucks, the genetic algorithm exhibits similar levels of performance at faster speeds. For larger instances of 30-50 trucks where the MIP is inadequate, the genetic algorithm still generates fuel saving results in under a minute. The trucks are routed on a network that includes 20 major German cities.

The area of convoy planning which involves routing a set of vehicles in convoys in a network provides some parallels to this platoon setting. Since this is mostly used in military applications where safety is crucial, the objective is usually to minimize the total movement time (Chardaire et al., 2005). The study by Valdés et al. (2011) can be seen as a special case where a transportation unit in a city needs to merge with a convoy that is travelling in a circular path across the city. They use dynamic programming to route the transportation unit to the convoy in an efficient way. The synchronized arc routing problem (Salazar-Aguilar et al., 2012) also shares some characteristics with the platoon planning problem. This problem also involves synchronizing the routes of multiple vehicles. Salazar-Aguilar et al. (2012) propose a local search heuristic to solve this NP-hard problem for large instances.

Again, platooning could create traffic congestion. This will occur if the number of trucks exceeds the capacity of a certain road segment. The area of traffic flow research could be used to look into this aspect. Traffic assignment models aim to minimize travel time in the system by assigning vehicles to specific links in the network. For examples, see Angelelli et al. (2016), Merchant & Nemhauser (1978).

2.4.2 Restricted platooning

Section 2.4.1 presents several studies that address different variants of the unrestricted platoon planning problem. It is, however, not clear if the solution approaches developed for these unrestricted settings would also be effective in the more restricted settings. Certain restrictions may be exploited by making use of specialized algorithms. For instance, Agatz et al. (2011) are able to solve large instances of the ride-sharing problem to optimality by restricting the number of riders per ride-share match. Nevertheless, the introduction of restrictions may also complicate matters as it makes it more difficult to find feasible solutions.

2.4.2.1 Restricted platooning - fixed routes

This setting also represents a scheduling problem where we need to determine the departure times/speeds of trucks given predetermined routes. Here, restrictions such as the ones relating to the platoon size or number of platoons per trip (see figure 2.3) need to be taken into account.

We are aware of one study that explicitly considers this setting. Meisen et al. (2008) aim to find profitable truck platoons given a set of routes. They set the maximum size of the platoon to be either two or four. To determine if a platoon is profitable (has net savings), they consider multiple criteria such as common distance, waiting time, fuel consumption etc. They propose a data mining based heuristic to solve this problem. The trucks are first categorized based on characteristics such as their load. Among these trucks, grouping possibilities are determined based on the trucks' physical characteristics. Within these trucks that are grouped together, platoons are planned based on the overlap in the routes. In addition to the fuel costs, the costs associated with waiting are also considered. To limit the exponential growth in the number of profitable platoons with an increase in the number of routes, they set upper limits on the waiting time, and lower limits on common distance and profit per platoon. To test the algorithm, the authors use synthetic datasets with up to 5000 routes

Other areas of research are similar to this setting. For example, Dumas et al. (1990) for an example of a fixed route scheduling problem. Also, the route overlaps may also be found based on algorithms used for solving the well-known longest common subsequence problem in computer science which, as the name suggests, involves finding the subsequence of maximum length that occurs in a set of given sequences (see Iliopoulos & Rahman (2008) for more information).

If we aim to reduce the inconvenience or waiting times for the trucks to form platoons, this setting resembles the area of schedule synchronization in public transit (see Wong et al. (2008); Daduna & Voß (1995); Voß (1990); Domschke (1989) for examples) where the goal is to minimize the total waiting time or inconvenience for passengers while considering transfers.

2.4.2.2 Restricted platooning - flexible routes

In this setting, we need to determine the routes of the trucks in addition to the schedules/ speeds of the trucks while taking different restrictions into account. While this platoon setting is the most general and realistic, we are not aware of any study that explicitly studies this setting. However, there are similarities with other well-known problems especially when we consider platoons of at most two trucks. Two-truck platoons are likely to be prevalent particularly in the initial stages of deployment.

If we consider the setting where each truck may be part of one platoon per trip, then for each pair of trucks, a platoon is feasible if it results in net savings for both the trucks i.e, the costs of driving in a platoon are lower than the costs of driving alone. This involves solving the routing problem for each pair of trucks. Given all feasible platoons, the assignment that maximizes the total system-wide savings can then be found by solving a general matching problem. Note that, unlike in unit capacity pick up and delivery problems (see Amey (2011); Berbeglia et al. (2007)), this problem does not represent a bipartite matching problem as we do not have two disjoint sets of trucks to match.

The two-truck platooning problem is similar to the ride-sharing problem with meeting points in which riders are willing to walk to a meeting point to shorten the detour for the driver. As in truck platooning, riders and drivers have to find the optimal points to start and end their joint trip. That is, both entities that are involved in the combined trip can move independently. Stiglic et al. (2015) design and test an algorithm for large-scale ride-sharing systems with meeting points. They consider meeting points that are within walking distances of the riders' present locations. A similar setting in the context of buses is considered by Mukai & Watanabe (2005). They allow for flexible pick up and drop off points of the customers and minimize the sum of the walking time, waiting time and the riding time.

When we relax the restriction on the number of platoons per trip, the problem is similar to the single-rider ride-sharing problems in which a driver can sequentially pick up multiple riders in the same trip. Chen et al. (2016a) consider meeting points and also rider transfers between drivers. They allow flexible roles for the participants within a car i.e., participants with a car can also ride with others. As a result, return restrictions are also incorporated. In Aivodji et al. (2016), apart from walking, riders may also take public transportation to reach the meeting point. This incorporation of movement of the riders strengthens the link to platooning where both the entities i.e., trucks that need to be matched are moving.

Ride-sharing is a special case of the well-known general pick up and delivery problem. The general pick up and delivery problem (Savelsbergh & Sol, 1995) considers vehicles that need to fulfil transportation requests by picking up goods at their origins and delivering them to their destinations. This can be extended to truck platooning where instead of goods, trucks need to be "picked up". Unlike the traditional pick-up and delivery problem, there are no fixed start and end locations defined as both vehicles are mobile. This is linked to

Table 2.3: Classification of platooning literature

	Flexible routes	**Fixed routes**
No restrictions on platoons	Sokolov et al. (2017) Nourmohammadzadeh & Hartmann (2016a) Larson et al. (2016) Larsson et al. (2015) Larson et al. (2013)	Zhang et al. (2017)* Liang et al. (2016) Van de Hoef (2016) Liang et al. (2014)
Restrictions on platoons		Meisen et al. (2008)

* special case/ sub-problem

the vehicle routing problem with roaming delivery locations. This problem considers the deliveries of shipments to the trunk of a customer's car (Reyes et al., 2017).

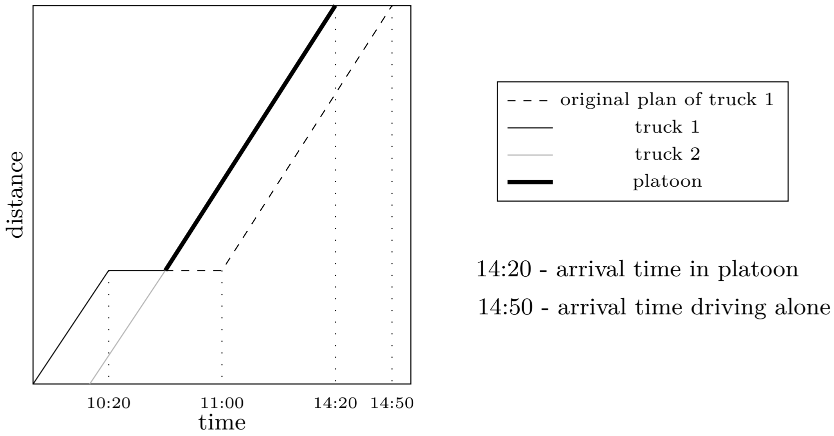
Conceptually similar problems are also seen in multi-modal freight transportation. Heeswijk et al. (2016) consider inter-modal networks with terminals where freight coming in by truck is consolidated and moved to a different terminal by barge, rail or truck from where the freight is sent to its destination. In the context of platooning, the meeting and split points of trucks may be conceptualized as the two terminals. If we consider a special case where all the trucks are headed to the same destination, the problem is linked to the merge in transit method of operation seen in parcel deliveries (see Croxton et al. (2003)).

Furthermore, as platooning involves synchronizing the routes of different trucks it is related to the area of vehicle routing with synchronization constraints. A survey of problems and related solution methods in this area may be found in Drexl (2012). In this area of problems, there is an interdependence in the routes of different trucks. Of the different types of synchronization described by Drexl (2012), *operation synchronization* is specially relevant for truck platooning. Operation synchronization refers to the spatial and temporal offsets allowed for different trucks to begin certain tasks, for example, depart from a depot. This is directly related to the route and time flexibilities.

Table 2.4 provides an overview of the methods and instances considered by the various studies.

2.5 Levels of human involvement in platooning

Up to now, we have considered platoons between trucks that require fully engaged drivers. As technology develops and legislation permits, driverless platoons may become possible in the future. The required level of human involvement is likely to gradually decrease as automated driving technology evolves. Since the widely-used SAE levels of driving automation (SAE International, 2016) focus on individual vehicles and do not consider platooning, we propose the following new classification to describe different levels of human involvement in platooning.



14:20 - arrival time in platoon

14:50 - arrival time driving alone

Figure 2.5: Increased productivity when the driver of truck 1 can take a break in a platoon

- Human driven platooning with in-platoon resting
- Hybrid platooning
- Driverless platooning

These different types of platooning give rise to new planning problems that we discuss in this section.

2.5.1 Human driven platooning with in-platoon resting

In this type of platooning, the following trucks can handle all the driving tasks which means that the drivers may rest while being in the truck. Therefore, this setting allows for more efficient utilization of the drivers. For this to be implemented in practice requires both technological feasibility and legal clearance.

Legal stipulations also limit the amount of time that a driver is allowed to drive. That is, truck drivers in most countries are subject to limits on their driving times before being required to take a break. The regulations depend on the type of vehicle and the country. For example, EU regulations state that a driver must take breaks totalling at least 45 minutes after a maximum of 4.5 hours of driving (Government-UK, 2016). Similarly, in the US, a break of 30 minutes is required after at most eight hours after a driver begins his duty (Goel, 2014). Regulations typically also prescribe weekly limits in addition to the limitations within a day. See Goel (2014); Goel et al. (2012); Goel & Rousseau (2012); Goel (2010) for a detailed overview of different regulations. In this setting, the time as the follower in the platoon would not count as formal driving time.

Allowing breaks during a platoon will relax break-time constraints and as such improve the overall transport efficiency. In particular, it may help increase the productivity of the drivers as they can cover more distance in the same time. Figure 2.5 illustrates the benefits of being able to take a break within the platoon. The example considers two trucks that share a portion of their route. Truck 1 starts a 40 minute break at 10:00. Ten minutes into his break, truck 2 arrives at the location. Instead of waiting to finish his break, the driver of truck 1 can now finish the last 30 minutes of his break as a following truck of the platoon and arrive half an hour earlier at his destination. Therefore, there is an improvement in the transit time and associated costs.

The example described in figure 2.5 considers a two truck platoon where each truck is part of only one platoon in its trip. The same idea can fairly easily be extended when we consider platoons of more than two trucks. Just like the example, the change will affect only the trucks in that platoon. It is, however, more complicated when a truck may be part of multiple platoons per trip. Since the different platoons in a trip are interdependent, any change made to the break of one truck will affect all the platoons in the trip of that truck and, in turn, all the platoons in the trips of the trucks part of the said affected platoons and so on. Therefore, the problem's computational complexity grows rapidly.

At the same time, there is an additional layer of complexity that needs to be considered in planning the platoons. Since breaks are allowed only for the drivers in the following trucks, the position of a truck in a platoon becomes an important planning decision. For longer trips, we could switch the order periodically so that all drivers get an opportunity to take a break. To plan the timing of switches in the platoon sequence, the timing of breaks, and travel times need to be considered. In these settings, time-related costs will probably be more relevant than fuel related costs. As a result, we may see an increase in the total system-wide travel distance which are compensated for by the savings in time.

2.5.2 Hybrid platooning

In this type of platooning, only the leading truck requires a human driver and the following trucks can be driverless. This means that the driver of the following truck is no longer required for parts of the trip, which may lead to labour cost savings (Kilcarr, 2016). Unless the leading and following truck have exactly the same itinerary (and following trucks basically serve as trailers), the following trucks would still need drivers for the first and last part of their trips when they are driving alone. As a result, the formation or dissolution of platoons requires specific points and can no longer be done en-route. Drivers could be moved between these points by taxi. The planning of these taxi rides gives rise to a pick-up and delivery problem of drivers.

The pick-up and delivery problem is a well known optimization problem, see for example, Berbeglia et al. (2010); Savelsbergh & Sol (1995). A special case of pickup and deliveries that involves people is referred to as the Dial-a-Ride Problem (Cordeau & Laporte, 2007). This is also similar to the last/first mile problem seen in scheduled public transit. The first mile problem is similar to the car pooling problem where multiple users are picked up and transported to a common flexible destination which could be any point on a public transportation line (see Minett (2013)). The last mile problem considers the opposite scenario where people are picked up from the public transportation line and taken to their destinations (see Wang & Odoni (2014); Cheng et al. (2012)).

Hybrid platooning also gives rise to new opportunities with regards to driver roles. The drivers may have different duties such as a platoon leader or a last mile driver. Furthermore, during the pick up and delivery of drivers, drivers may swap roles. The driver dropped off may take over as the leading driver of the platoon while original platoon leading driver may take over the decoupled truck and complete its final leg. This is specially relevant for the planning of shifts and breaks. This is linked to the general area of crew scheduling (see Ernst et al. (2004); Raff (1983)). Vehicle routing and crew scheduling has been done in parallel in most of the literature (see Hollis et al. (2006) for an overview). Drexl (2011) mentions that the truck and trailer approach could also be used in this way. The drivers may be considered vehicles which can couple with a truck that is left at intermediate locations.

Apart from being picked up by a driver, a truck could also be picked up by another platoon. Also, drivers could pick up trucks from one location and leave it at another location where the truck is then picked up by another platoon. These two basic arrangements may be combined in any order and form. Therefore, there is quite some flexibility in the planning of hybrid platoons. On that account, following trucks can essentially act as trailers that need to be picked up and dropped off. Therefore, this problem is related to the truck and trailer problem (see Derigs et al. (2013); Villegas et al. (2013); Chao (2002)) and the swap body vehicle routing problem (see Lum et al. (2015); Absi et al. (2017); Miranda-Bront et al. (2017); Huber & Geiger (2014)). Meisel & Kopfer (2014); Drexl (2011) categorize transport means as active and passive. Active means are also allowed to transfer load onto passive means in addition to picking them up. In this platooning context, a truck could either be active or passive depending on its use at a particular instant.

2.5.3 Driverless platooning

This form of platooning involves completely driverless trucks which provides a greater degree of flexibility since the platoons do not have human drivers that need to go home or take breaks. The planning of driverless platoons is similar to the planning of regular human-driven platoons but the additional flexibility creates more possibilities to maximize platooning benefits. For instance, the absence of drivers means that trucks do not have to return to a fixed location. This means that the truck could go to a different depot than its starting depot if it results in more platooning opportunities now or on the next trip.

2.6 Real-time platoon planning

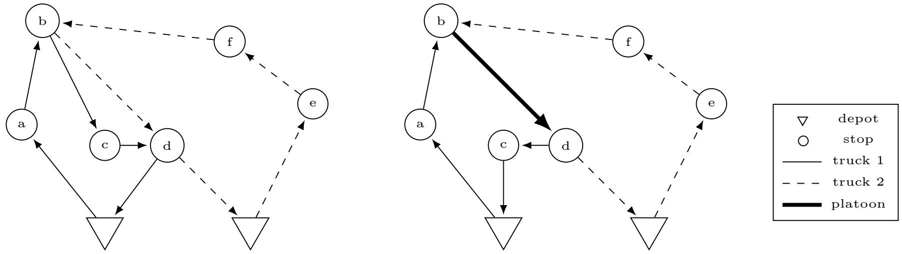
In our discussion up to now, we assumed that all the information required for planning the platoons is known in advance and accurate. However, in practice, trucks may continuously arrive and withdraw from the platoon planning system thereby changing the state of the system.

The dynamics increase the complexity of the decision making process. It requires real-time information of the positions of all vehicles and communication methods to inform the vehicles of any changes. Decisions need to be made quickly as trucks are en-route which means that platooning opportunities at one point in time may no longer be possible at a later point in time. This dynamism links this problem to the area of dynamic vehicle routing in which route plans may be adjusted when new information becomes available (see for example Pillac et al. (2013)).

Dynamic planning could be carried out in a time-based or an event-based manner (see Agatz et al. (2011)). A well known example of a time-based approach is the rolling horizon approach where optimization is repeated after a given time interval. Instead of the optimization being repeated after a certain time, it also could be triggered by an event such as the arrival of a new entity as the system. This is the case with event-based planning and is considered by Van de Hoef (2016) and Larson et al. (2013) who repeat the optimization when new information becomes available.

Adler et al. (2016) look at a case of real-time platooning of multi-truck platoons from a queueing perspective by considering a Poisson-distributed series of vehicles arriving at a particular station where they form platoons and head to a common destination. They look at the trade-off between platoon savings and delay due to waiting. Two sets of platoon formation policies are defined - all the trucks at the station leave as a platoon when either a certain time period has elapsed or a threshold platoon size is reached. On comparing these two sets of policies, they observe that the performance is dependent on the size of the platoons produced. The threshold platoon size policies allow an average of one truck more per platoon than the time table policies. As a consequence, the threshold policies perform better in terms of the energy saved for a given delay.

Based on historical information, we may have some probabilistic information about future events. For instance, historical data could provide an indication about trip announcements from freight transporters. For instance, if some trucks traverse the same route regularly, it is likely that they can form platoons. The availability of probabilistic information links the problem to the area of stochastic vehicle routing (Gendreau et al., 1996). See for example, Bent & van Hentenryck (2004) and Powell (1996) for the usage of stochastic information in dynamic settings. Furthermore, the travel times of trucks could be uncertain due to the weather, traffic amongst other factors (van Lint et al., 2008). For examples of routing



No platooning opportunity Platooning opportunity between stops *b* and *d*

Figure 2.6: Changing the sequence of stops to create a platooning opportunity

problems with stochastic travel times, see Kenyon & Lyons (2003); Laporte et al. (1992). In the context of platooning, this was considered by Zhang et al. (2017) as described in Section 2.4.2.1.

2.7 Vehicle routing with platooning

Instead of planning only single trips from one origin to one destination, it is also possible to consider platooning opportunities for routes with multiple stops. It may be possible to exploit the flexibility in the sequence of stops to create new platooning opportunities as shown in Figure 2.6. The figure shows the routes of two trucks that each serve four different locations. Initially, there is no common path in their routes and, therefore, no opportunities to platoon. However, by switching the order of stops *c* and *d* on route 1 gives rise to a platooning opportunity between stops *b* and *d*.

This possibility combines platoon planning with vehicle routing. There is a large body of research on solution approaches for the vehicle routing problem (VRP). Laporte (1992) provides an overview of these different approaches. The VRP aims to minimize the costs of serving a set of customer using a fleet of vehicles with limited capacity.

When all trucks belong to the same fleet or company, the problem can be solved by considering a VRP that incorporates platooning opportunities. One important difference with a standard VRP is that we need to consider multiple paths between pairs of points to identify platooning opportunities. Another difference is that in platooning the different trucks would typically be located at different depots. This links the problem to the multi-depot VRP (see Crevier et al. (2007); Lim & Wang (2005); Cordeau et al. (1997); Renaud et al. (1996)).

Within the fleet of a single truck operator it may even be possible to change the assignment of stop locations to vehicles to facilitate truck platooning. This is obviously not possible if several different truck operators are involved. In this case, the route cluster can be assumed fixed, similar to a cluster first, route second heuristic (see Prins et al. (2014)). Here, the customers are clustered together and the customers in a cluster are visited by the same

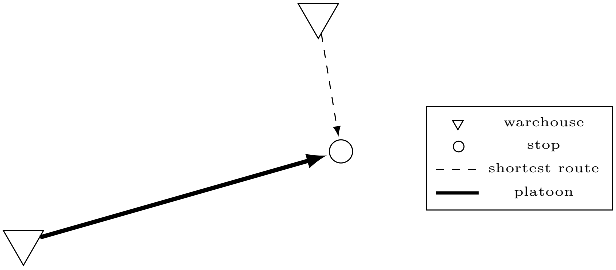


Figure 2.7: Change in order assignments because of platooning

truck. The routing phase can be treated as solving a TSP with TW within each cluster (Laporte et al., 2000).

2.8 Network design and platooning

The previous section described how platooning could have an impact on the way that freight is routed through the network at an operational level. Platooning could impact at strategic and tactical level decisions as well.

The strategic level decisions involve long term aspects such as physical network design (Crainic, 2000). For instance, parts of the network may be heavily used by platoons and require infrastructural changes such as reinforcement of roads, new lanes, additional communication support in tunnels etc. see e.g., Chen et al. (2017, 2016a). Also, since the starting locations of trucks influence platooning opportunities, there is an incentive to move facilities such as warehouses and depots closer to each other. This relates to the concept of economies of agglomeration (see Glaeser (2007)).

Tactical level decisions relate to service network design which involves decisions mainly pertaining to the organization of services, and the routing of freight. Crainic (2000) provides an overview of research in this area. It may be beneficial to assign a shipment to a warehouse location that is farther away to create more platoons. Figure 2.7 shows a simple example of such a situation. The flexibility of platooning means that this decision should be made as late as possible based on real-time platooning opportunities on the different routes. Xu et al. (2009) look at a similar problem in the e-commerce setting citing the dynamic nature of the system. This dynamic nature also creates a link with the dynamic service network design problem (see DallOrto et al. (2006)). Additionally, we can view the flexible formation of a platoon as an instantaneous switch in the transportation mode. This links platooning to the multimodal network design problem (for an example, see Yamada et al. (2009)).

Table 2.4: Overview of platoon planning literature

Author(Year)	**Solution method**	**Network used**	**Largest instance size**
Zhang et al. (2017)	Exact	Artificial - single road, junction	2
Sokolov et al. (2017)	Exact	Artificial - 10 X 10 grid	50
Larson et al. (2016)	Exact	Artificial - 10 X 10 grid, Real-life - Chicago highway network	25
Liang et al. (2016)	Heuristic - local search	Real-life - single Swedish highway	2
Van de Hoef (2016)	Exact, Heuristic - local search	Real-life - Swedish mainland	5000
Nourmohammadzadeh & Hartmann (2016a)	Exact, Heuristic - genetic algorithm	Real-life - Twenty German cities	50
Adler et al. (2016)	Analytical - queueing theory	Artificial - single road	N/A *
Larsson et al. (2015)	Exact, Heuristic - local search	Real-life - German autobahn network	200
Liang et al. (2014)	Heuristic - local search	Real-life - region in Europe	1800
Liang et al. (2013)	Analytical - fuel model	Artificial - single highway	2
Larson et al. (2013)	Exact, Heuristic - local search	Real-life - German autobahn network	8000
Meisen et al. (2008)	Heuristic - truck platoon sequential pattern algorithm (based on pattern growth)	Real-life - Two German zip codes	5000

*use an arrival rate of trucks

2.9 Conclusions and future research

Truck platooning can be seen as the first step towards automated driving in an open environment. Truck platooning has the potential to provide cost savings and is associated with several societal benefits. To efficiently reap the benefits of platooning requires appropriate planning and optimization approaches.

This chapter outlined various planning challenges encountered in platoon planning. Also, the chapter provided an overview of relevant operations research models from different areas. Table 2.4 provides an overview of the platoon planning literature discussed in this chapter. From tables 2.1, 2.3, and 2.4, we see that there are several papers that address various problems but approaches to deal with the dynamic, advanced, and restricted forms of platooning etc. are still lacking. More specifically, the areas for future research include -

Optimization. All studies acknowledge that the different platoon planning problems are difficult to solve. Table 4 shows that most studies resort to similar kinds of basic local search heuristics on relatively small problems. One interesting direction for future research is to study the effectiveness of more sophisticated meta-heuristics (see Cordeau et al. (2002); Bräysy & Gendreau (2005a,b)) such as tabu search and simulated annealing in solving real-life platoon planning problems. To allow the systematic comparison of the different solution approaches, we would require the introduction of standard benchmark instances.

Another interesting direction for future research is the development of specialized solution methods to handle the various restrictions such as those relating to platoon size. Given that these restricted settings are the most likely to occur in reality especially in the initial phases of deployment, research in the area is required.

Higher levels of automation reduce the level of human involvement and therefore open up a set of new planning problems. We are not aware of any research in this area so far.

Dealing with uncertainty. Areas relating to real time planning are of interest. In practice, the information continuously changes with trucks entering and leaving the system. Also, travel time uncertainty represents a realistic scenario but is more complex to solve and implement. Zhang et al. (2017) do study stochastic travel times but in a small setting. Moreover, we are not aware of any research dealing with stochastic and dynamic arrivals of trucks for platooning.

When we consider real-time planning, congestion could also be taken in to account as a result of too many trucks being routed on the same links. A few trucks could be routed differently to increase the benefits for the whole system. Other traffic also needs to be considered when this approach is used. This is conceptually related to the area of traffic assignment and multimodal service network design.

System sustainability. With a very small number of participants, the chances of formation of platoons go down. To ensure that platooning is sustainable in the long run, several ‘special’ steps might need to be taken during the initial phases of implementation.

From the planning perspective, maximization of the number of companies involved could be a way to go. Incentive schemes from the government to ensure benefits could also play a role. For examples, these incentives could be to subsidize the technology or provide special cost cuts for platoons. The determination of such measures and their effects on the system are interesting areas to look into.

Also, to ensure system sustainability, ways to ensure fair participation and prevent strategic behaviour are necessary. Participants may try to maximize their own profit rather than contributing to the system benefits. Designing mechanisms such as rating systems etc. to prevent this is required.

Network design. Platooning could have implications for the transport and supply chain network designs. As discussed, parts of the transport network may require upgrading to reap the maximum benefits of platooning. Similarly, supply chain network decisions such as locations of facilities might be made differently with platooning in the scene.

These network changes require significant investments and therefore, the expected costs and benefits will have to be carefully weighed against each other. Moreover, as the level of human involvement becomes less, the magnitude of the effects will change due to the additional benefits.

Incentives could again play a role here. Given the societal benefits of platooning, the government may want to encourage some of the (expected) effects so that forming platoons becomes easier. Additional research into the effects of platooning on the network will help this cause.

Given the promising potential of platooning, we are optimistic that this review will prompt new research contributions to the area.

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3 Spatial and temporal synchronization of truck platoons

3.1 Introduction

Truck platooning technology allows trucks to virtually connect and automatically drive in close formation. The short headways decrease air drag and thereby fuel consumption. By saving fuel, platooning can contribute both to costs savings and lower vehicle emissions (Scora & Barth, 2006). Other benefits of platooning include improved road capacity utilization and traffic throughput (Schladover et al., 2015; Van Arem et al., 2006; Lioris et al., 2017). Moreover, as the following trucks break and steer automatically with the leader truck in front, there is a lower risk of rear-end collisions. Additional cost savings may be possible in the future when the following trucks in a platoon can operate without drivers (Kilcarr, 2016) or the drivers in the following trucks can take breaks to comply with legal work-time restrictions.

Truck manufacturers across the world have conducted real-world tests with truck platooning (Bhoopalam et al., 2018). So far, most of these tests focus primarily on technological challenges related to making the trucks drive in tandem (Bergenhem et al., 2012a). Equally important are the challenges related to the planning and execution of platoons. Careful planning is especially important when the truck density is low or when the density of trucks with compatible platooning technology is low. In such cases, it is unlikely that we can form platoons spontaneously and achieve comparable benefits as when these platoons would be planned in advance (Sokolov et al., 2017; Liang et al., 2014). Another reason that careful planning is important is that the potential fuel savings of platooning are relatively small, i.e., between 4 percent and 13 percent (McAuliffe et al., 2018).

The planning of platoons involves determining the paths and time schedules of a set of trucks, each with a single origin and destination, with the objective to minimize the system-wide travel costs. We refer to the associated planning problem as the Platoon Routing Problem with Time Windows or the PRP-TW. We define a *platoon* as a set of two or more virtually connected trucks that drive together at short headways. Legal restrictions will limit the maximum number of trucks in a platoon. For example, the maximum platoon size was limited to two for tests in Kentucky and Missouri (Goble, 2018). The reason for this is that larger platoons may disrupt traffic flows at highway on- and off-ramps (Calvert et al., 2019; van Maarseveen, 2017).

One truck can potentially join different platoons along its journey. This creates inter-dependencies in time and space between different platoons. These inter-dependencies make the planning and coordinating of platoons more challenging. In fact, Larsson et al. (2015) show that these inter-dependencies make the Platoon Routing Problem NP-hard, even without deadlines and when all trucks start at the same origin.

In this chapter, we model and solve the platoon routing problem with time windows (PRP-TW) but will specifically focus on finding fast solution methods for problem settings in which two trucks platoon together and all trucks are in at most one platoon per trip. We refer to the planning problem that corresponds to this special case as the *Platoon Pair Routing problem with time windows (PPRP-TW)*. Here, we also look at the case without time windows or the PPRP to gain further insights. As the PPRP-TW setting only requires coordination between two trucks, the issue of inter-dependencies is smaller and we therefore believe that these platoons are easier to implement in practice and more robust in the face of travel time variability. We evaluate the effectiveness of these smaller platoons.

The main contributions of this chapter can be summarized as follows. First, we present polynomial time approaches to determine the routes and time schedules of two-truck platoons by studying both the PPRP-TW and the PPRP. Second, we introduce a novel mathematical programming formulation for the PRP-TW that involves larger platoons and multiple platoons per trip. Third, we present several fast heuristics based on the polynomial time approaches for the PPRP that provide high-quality solutions. Finally, we conduct numerical experiments to evaluate the advantages and disadvantages of restricting the number of platoons trucks can join on their journeys and the number of trucks per platoon.

The remainder of the chapter is organized as follows. In Section 3.2, we review the relevant literature. In Section 3.3, we define the PRP-TW and provide some useful properties. Section 3.4 presents a Mixed Integer Programming formulation for the PRP-TW. In Section 3.5, we focus on the PPRP-TW. Section 3.6 presents two heuristics and an improvement procedure for the PRP-TW based on the insights from the PPRP-TW and the PPRP. Section 3.7 presents the results of our numerical experiments. Finally, Section 3.8 summarizes our conclusions and outlines directions for future research.

3.2 Related literature

There has been growing interest in studying the planning and operations pertaining to the application of automated driving technology not just on roads (Mahmassani, 2016), but also on water (Colling & Hekkenberg, 2020), air (Richert & Cortés, 2013), and even a mix of roads and air, for example, with drones (Poikonen & Golden, 2020; Poikonen et al., 2019;

Otto et al., 2018). In this section, we restrict ourselves to platooning and discuss the most relevant and recent literature on truck platoon planning. Bhoopalam et al. (2018) provide a more extensive overview.

A number of papers focus on platoon planning in which trucks travel on a fixed path, thus ignoring any possible routing flexibility. These papers typically focus on a single highway lane or designated hub (Adler et al., 2016; Larsen et al., 2019). A number of these specifically focus on adjusting speeds to form platoons (Liang et al., 2013; Sun & Yin, 2019). Others have focused more on different platooning cost functions (Boysen et al., 2018) or travel time uncertainty (Zhang et al., 2017) or dynamic planning (Van de Hoef, 2018).

In line with our chapter, others do incorporate the route planning of the trucks. Larson et al. (2013) set a threshold for the detour a truck can make. They consider a traffic junction and evaluate whether it would be beneficial for approaching trucks to adjust their speed(s) to form a platoon together. They propose a pairwise merging heuristic in which they continuously merge the most beneficial platoon pairs to generate multi-truck platoons and show that the platooning savings increase when trucks can make a detour.

Larsson et al. (2015) also use such a pairwise heuristic for a centralized setting on a network. Here, they ignore deadlines or time constraints. In addition to this pairwise heuristic, they also present a hub heuristic which groups trucks based on their likelihood of traversing a certain edge. They formulate a MIP to evaluate their heuristics. In their subsequent work, Larson et al. (2016) focus on reducing the problem size by defining additional constraints on aspects such as the detour, which they use to set certain decision variables to zero. As a next step, Luo et al. (2018) extend the model from Larson et al. (2016) by allowing trucks to have different speeds on different edges. Nourmohammadzadeh & Hartmann (2016b) also formulate a MIP which they use to evaluate a genetic algorithm based meta-heuristic, and then an ant-colony optimization meta-heuristic (Nourmohammadzadeh & Hartmann, 2019).

Albinski et al. (2020) look at the effect of introducing regulations on driver rest times. They formulate a MIP and present a pre-processing procedure to reduce the problem size. They consider different levels of driver involvement and notice that the platoon savings vary greatly.

None of these studies explicitly focus on simple 2-truck platoons with flexible routes and how they compare with larger platoons. As mentioned earlier, these 2-truck platoons have multiple benefits and we focus our attention toward evaluating them in this chapter.

3.3 Problem definition and properties

We now define the PRP-TW. Following this, we describe a couple of theoretical properties relevant to the PRP-TW.

3.3.1 Problem definition

We model the PRP-TW on a graph $\mathcal{G} = (\mathcal{V}, \mathcal{A})$ with non-negative arc lengths in which the costs of traversing arc $a \in \mathcal{A}$ is c_a. Let c_{uv} denote the shortest path distance between nodes $u, v \in \mathcal{V}$. Consider a set of trucks $\mathcal{K}$ in which truck $k \in \mathcal{K}$ has origin $o_k \in \mathcal{V}$ and destination $d_k \in \mathcal{V}$. A truck can save (fuel) costs by driving together in a platoon with one or more other trucks. Let $\rho \in (0.5, 1)$ be the average fuel consumption factor for a truck in a platoon. The fuel costs for a single truck driving in a platoon on arc a are ρc_a, where $1 - \rho$ represents the fuel savings for a truck in a platoon as compared to driving alone. Note that ρ is greater than 0.5 as the total combined fuel consumption of a 2-truck (or larger) platoon cannot be less than the fuel consumption of a truck driving alone. As is common in the literature (see for example Nourmohammadzadeh & Hartmann (2016b); Larsson et al. (2015)), we consider the costs savings to be independent of its position in the platoon. Furthermore, we assume that trucks in a platoon share the savings equally. Therefore, the parameter ρ captures the average savings of each truck in the platoon and abstracts away from different savings for leaders and followers. The total combined cost of a n-truck platoon traversing a is $c_a^n = n \cdot \rho \cdot c_a$. Note that, we will always have $c_a^n \leq c_a^{n+1}$ as the addition of an extra truck can never decrease costs.

Each truck specifies an earliest departure time a_k from the origin and a latest arrival time l_k at the destination. Each truck travels at the same constant speed. This reflects the fact that trucks often drive at approximately the maximum allowable speed on a road segment and can not safely or legally drive faster or slower. Let t_{uv} be the shortest travel time between nodes u and v. Let the latest departure time $\bar{a}_k$ denote the latest time that the truck can leave the origin to reach the destination in time. The time flexibility f_k of truck $k \in \mathcal{K}$ is the difference between the earliest and latest departure time or $f_k = l_k - a_k - t_{o_k d_k}$. This flexibility specifies the maximum possible waiting and detour time within a trip.

We assume that trucks can not stop and wait along an edge, that is, trucks can only wait at nodes. This, along with our assumption that trucks travel at the same constant speed means that platoons are only formed (or dissolved) at nodes.

Given a set of trucks, the truck platooning problem involves finding the path and time schedule of all trucks so as minimizing costs to arrive at their destinations before their deadlines. This also includes finding which truck platoons with which. Note that we only consider which trucks form a platoon and not focus on which truck will act as the leader and follower in the platoon.

We can restrict the PRP-TW to allow at most $N \in \mathbb{N}_{\geq 2}$ trucks per platoon and at most $M \in \mathbb{N}$ platoons per truck trip. We use (N, M) to denote a setting with these constraints.

3.3.2 Basic properties

In this section, we outline a few useful properties of feasible and optimal truck platoons. First, we can eliminate meeting points and split points for which the detour would be too long to offset the potential savings.

Property 1. *Let* c_{uv} *denote the shortest path length between nodes* u *and* v*. Given fuel consumption factor* ρ*, a set of trucks* $\mathcal{K}' \subseteq \mathcal{K}$ *with* $|\mathcal{K}'| > 1$ *can feasibly form a platoon together at meeting point* m *only if* $\rho < \frac{\sum_{k\in\mathcal{K}'} c_{o_k d_k} - \sum_{k\in\mathcal{K}'} c_{o_k m}}{\sum_{k\in\mathcal{K}'} c_{m d_k}}$.

Proof. Consider the case where the trucks all meet at a single m. In this case, their platooning costs will at least be $\sum_k c_{o_k m} + \rho \cdot \sum_k c_{m d_k}$. For this platooning solution to be beneficial, we need

$$\sum_k c_{o_k m} + \rho \cdot \sum_k c_{m d_k} < \sum_k c_{o_k d_k}$$

$$\rho \sum_k c_{m d_k} < \sum_k c_{o_k d_k} - \sum_k c_{o_k m}$$

$$\rho < \frac{\sum_k c_{o_k d_k} - \sum_k c_{o_k m}}{\sum_k c_{m d_k}} \square$$

Note that a similar property holds for split point s: $\rho < \frac{\sum_k c_{o_k d_k} - \sum_k c_{s d_k}}{\sum_k c_{o_k s}}$.

Second, we can eliminate some platoons due to incompatibility of the earliest departure and latest arrival time of the different trucks.

Property 2. *A set of trucks* $\mathcal{K}' \subseteq \mathcal{K}$ *with* $|\mathcal{K}'| > 1$ *can never be in a platoon together if the* latest *earliest departure time of the trucks is later than the* earliest *latest arrival time of the trucks, i.e.,* $\max_{k\in\mathcal{K}'} a_k > \min_{k\in\mathcal{K}'} l_k$*.*

Proof. Consider a set of trucks $\mathcal{K}' \subseteq \mathcal{K}$ with $|\mathcal{K}'| > 1$ that start traveling together in a platoon at time t. By definition $\max_{k\in\mathcal{K}'} a_k \leq t \leq \min_{k\in\mathcal{K}'} l_k$. This provides a contradiction if $\max_{k\in\mathcal{K}'} a_k > \min_{k\in\mathcal{K}'} l_k$. $\square$

Finally, when the maximum platoon size is greater than two, it is always possible to make platoons for all trucks that jointly traverse an arc. Moreover, for certain cost structures, the total system costs will remain the same no matter how the trucks are allocated to platoons.

Property 3. *If the cost savings per truck do not depend on the size of the platoon and the maximum platoon size is* $N \geq 3$*, all trucks that jointly traverse an arc will be part of a platoon in an optimal solution*

Proof. Consider k trucks that jointly traverse an arc a. If k is an even number, trucks can be matched into $\frac{k}{2}$ 2-truck platoons. If k is an odd number, the trucks may be matched into $\frac{k-3}{2}$ 2-truck platoons and one 3-truck platoon. Therefore, trucks jointly traversing arcs can always be organized into platoons, which brings down total costs as compared to some of them driving alone. Therefore, in an optimal solution all these trucks will be in a platoon. $\square$

3.4 Mixed Integer Programming formulation

We model the PRP-TW on a graph $\mathcal{G} = (\mathcal{V}, \mathcal{A})$ by decomposing the problem into two phases. In the first phase, we focus on our primary goal of minimizing system costs by finding the minimum-cost paths of all trucks in the system. In the second phase, we find the specific platoons associated with these paths.

Phase 1 - Finding paths of trucks and platoons

The PRP-TW involves the synchronization of truck routes in both space and time. To capture the spatial dimension, we create multi-graph $\mathcal{G}_\mathcal{S} = (\mathcal{V}, \mathcal{A}_\mathcal{S})$ in which any pair of connected nodes $(u, v) \in \mathcal{G}$ is now connected by a set of parallel arcs of two types: (i) *solo* arcs and (ii) n-platoon arcs ($n > 1$). This captures the fact that trucks can travel between two nodes $(u, v) \in \mathcal{G}$ either alone or as part of a platoon of a specific size, each with a different cost.

To model time, we further modify $\mathcal{G}_\mathcal{S}$ into a time-expanded network $\mathcal{G}_\mathcal{T} = (\mathcal{V}_\mathcal{T}, \mathcal{A}_\mathcal{T} \cup \mathcal{H}_\mathcal{T})$ by discretizing the problem into time periods of equal length $\triangle$, meaning we have a set of time points $\mathcal{T} = \{0, \triangle, 2\triangle, 3\triangle, \ldots, H\triangle\}$. Note that the total number of time periods H is dictated by the latest l_k for truck $k \in \mathcal{K}$ as $H = \lceil \frac{max_{k\in\mathcal{K}} l_k}{\triangle} \rceil$. The time-expanded network $\mathcal{G}_\mathcal{T}$ therefore has a copy u_i of each node $u \in \mathcal{V}$ for each of the time points $i \in \mathcal{T}$ and so $|\mathcal{V}_\mathcal{T}| = (H + 1) \cdot |\mathcal{V}|$.

Like Boland et al. (2017), we split the arc set into two sets $\mathcal{A}_\mathcal{T}$ and $\mathcal{H}_\mathcal{T}$ for ease of explanation. An arc $a \in \mathcal{A}_\mathcal{T}$ connects two nodes $u_i, v_j \in \mathcal{V}_\mathcal{T}$ such that $j = i + \lceil t_{uv}/\triangle \rceil$. Travel along such an arc represents movement in both space and time. An arc $a \in \mathcal{H}_\mathcal{T}$ connects two nodes $u_{i\triangle}, u_{(i+1)\triangle} \in \mathcal{V}_\mathcal{T}$ which represents movement only in time, i.e., the truck waits.

Trucks only incur costs when they travel spatially, that is, there are no waiting costs. Hence, the cost of traveling on a *solo* arc a is c_a. Let binary variable x^{1t}_{ak} be 1 if truck k begins traversing solo arc a at t. The corresponding binary variable x^{nt}_{ak} takes a value of 1 if truck k begins traversing n-platoon arc a at t. On an *n-platoon* arc, there is a fixed cost c^n_a for each additional *n-platoon*. Let y^{nt}_a denote the maximum number of n-platoons that start traversing arc a at t. The number of trucks is therefore $n \cdot y^{nt}_a$, i.e., it can only increase in steps of n. The maximum value this variable can take is defined by $n \cdot y_a^{nt} \leq |\mathcal{K}|$ where $|\mathcal{K}|$ is the number of trucks in the system. If we fix the value of y_a^{nt}, the model can be characterized as a continuous time service network design problem (Boland et al., 2017)

Each arc a has the same travel time t_a for each truck, irrespective of whether the truck travels solo or in a platoon. We can then formulate a mixed integer program for phase 1 of the PRP-TW. Before doing so, we introduce some additional notation: $\delta^+(v)$ denotes the set of arcs originating from node v and $\delta^-(v)$ denotes the set of arcs ending at node v.

$$\min \quad \sum_{a\in\mathcal{A}_\mathcal{T}} \sum_{t\in\mathcal{T}} \Big(\sum_{k} c_a x_{ak}^{1t} + \sum_{n>1} c_a^n y_a^{nt}\Big) \tag{3.1}$$

$$\sum_{n=1}^{N} \sum_{a\in\delta^+(v)} x_{ak}^{nt} - \sum_{n=1}^{N} \sum_{a\in\delta^-(v)} x_{ak}^{n(t+t_a)} = \begin{cases} 1 & (v,t) = (o_k, a_k) \\ -1 & (v,t) = (d_k, l_k) \\ 0 & otherwise \end{cases} \qquad \forall v \in \mathcal{V}, t \in \mathcal{T}, k \in \mathcal{K} \tag{3.2}$$

$$\sum_{k} x_{ak}^{nt} \leq n \cdot y_a^{nt} \qquad \forall a \in \mathcal{A}_\mathcal{T}, 1 < n \leq N \tag{3.3}$$

$$x_{ak}^{nt} \in \{0,1\} \qquad \forall a \in \mathcal{A}_\mathcal{T} \cup \mathcal{H}_\mathcal{T}, k \in H, t \in \mathcal{T}, n \leq N \tag{3.4}$$

$$y_a^{nt} \in \mathbb{Z}^+ \qquad \forall a \in \mathcal{A}_\mathcal{T}, t \in \mathcal{T}, n \leq N \tag{3.5}$$

The objective function (3.1) minimizes the total costs of the system - the first term denoting the variable costs when trucks travel on solo arcs and the second term the fixed costs of taking a platoon arc. Constraints (3.2) are a set of flow constraints that ensure the timely departure and arrival of trucks at their origins and destinations respectively. Constraints (3.3) allow sufficient capacity on platoon arcs for trucks to make use of should it lead to the minimization of costs. Constraints (3.4) and (3.5) specify the domains of the decision variables.

We can simplify our general formulation to accommodate our specific symmetric platooning cost structure. Recall from Section 3.3 that we use a cost structure of the form $c_a^n = n \cdot \rho \cdot c_a$ for an n truck platoon. This means that the costs savings of driving in a platoon are not dependent on the position of the truck in the platoon. More generally, any number of trucks greater than two can be matched into platoons of at least size two in multiple ways without changing the total system costs (Property 3). This means we do not need different arcs for different platoon sizes and can merge the different n-platoon arcs into one general platooning arc. Therefore, we use c_a^p to denote the costs for a truck to travel arc a in a platoon *of any size*. Let w_{ak}^t be 1 if truck k begins traveling on solo-arc a by itself at t. Similarly let x_{ak}^t be the corresponding variable if truck k travels on a platoon-arc (of any size). We can then formulate the problem as -

$$\min \quad \sum_{a\in\mathcal{A}_\mathcal{T}} \sum_{t\in\mathcal{T}} \Big(\sum_{k} c_a w^t_{ak} + \sum_{k} c^p_a x^t_{ak}\Big) \tag{3.6}$$

$$\sum_{a\in\delta^+(v)} (w^t_{ak} + x^t_{ak}) - \sum_{a\in\delta^-(v)} (w^{t+t_a}_{ak} + x^{t+t_a}_{ak}) = \begin{cases} 1 & (v,t) = (o_k, a_k) \\ -1 & (v,t) = (d_k, l_k) \\ 0 & otherwise \end{cases} \qquad \forall v \in \mathcal{V}, t \in \mathcal{T}, k \in \mathcal{K} \tag{3.7}$$

$$x^t_{ai} \leq \sum_{k\neq i} x^t_{ak} \qquad \forall a \in \mathcal{A}_\mathcal{T}, i \in \mathcal{K}, t \in \mathcal{T} \tag{3.8}$$

$$w^t_{ak} \in \{0,1\} \qquad \forall a \in \mathcal{A}_\mathcal{T} \cup \mathcal{H}_\mathcal{T}, k \in \mathcal{K}, t \in \mathcal{T} \tag{3.9}$$

$$x^t_{ak} \in \{0,1\} \qquad \forall a \in \mathcal{A}_\mathcal{T} \cup \mathcal{H}_\mathcal{T}, k \in \mathcal{K}, t \in \mathcal{T} \tag{3.10}$$

The objective function (3.6) again seeks to minimize system-wide travel costs. Constraints (3.7) are again a set of flow constraints that ensure trucks leave their origin and arrive at their destination as per schedule. Constraints (3.8) ensure that a truck can travel on a platooning arc only if there is at least one other truck travelling on the same arc at the same time. Constraints (3.9) and (3.10) specify the domains of the variables.

When the maximum number of trucks allowed in a platoon is two, we need to include an additional constraint to ensure that an individual truck doesn't get routed on a platoon arc when there is, in fact, no room for it, that is, if all trucks on a platooning arc are already in platoons of size 2. We do this by introducing an additional variable to ensure that the number of trucks on a platooning arc stays even as $\sum_k x^t_{ak} = 2 \cdot z^t_a \forall a \in \mathcal{A}_\mathcal{T}, t \in \mathcal{T}$ where z^t_a is an integer variable.

Phase 2 - Finding specific trucks and platoons per path

Phase 1 determines the high-level flow of trucks throughout the network. As part of its output, it specifies the route and time schedules of each truck and whether the truck drives individually or as part of a platoon on each time-space arc along its route. However, it does not provide us with information on the platoon partners of each truck. In phase 2 of our approach, we formulate another MIP to generate specific platoons based on the output of phase 1.

There are many different possible specific platoons that can be created from the solution of stage 1. We aim to find the solution that minimizes the number of platoons in the system. The rationale behind this is that forming platoons is inconvenient for the associated trucks and the surrounding traffic.

Let $\mathcal{K}_a^t = \{i \in \mathcal{K} : x_{ai}^t = 1\}$ be the set of trucks on platoon arc a at time t. The set of feasible platoons on arc a and time t is $\mathcal{S}_a^t := \{\mathcal{S}' \subseteq \mathcal{K}_a^t : 2 \leq |\mathcal{S}'| \leq N\}$. This allows us to define $\mathcal{S}_{a(i)}^t := \{\tilde{\mathcal{S}} \subseteq \mathcal{S}_a^t : i \in \tilde{\mathcal{S}}\}$, which is the set of possible platoons that involve truck i. Let $\mathcal{S} = \cup_{a \in \mathcal{A}, t \in \mathcal{T}} \mathcal{S}_a^t$. Let y_{as}^t be a binary decision variable equal to 1 if platoon formation $s \in \mathcal{S}$ is used on arc a at time t. Similarly, let y_s be a binary decision variable equal to 1 if platoon formation $s \in S$ is used at least once. We can then formulate a mixed integer program as follows.

$$\min \sum_{s \in \mathcal{S}} y_s \tag{3.11}$$

$$\sum_{a \in \mathcal{A}_{\mathcal{T}}} \sum_{t \in \mathcal{T}} y_{as}^t \leq M y_s \qquad \forall s \in \mathcal{S} \tag{3.12}$$

$$y_{as}^t \leq x_{ai}^t \qquad \forall a \in \mathcal{A}_{\mathcal{T}} \cup \mathcal{H}_{\mathcal{T}}, t \in \mathcal{T}, s \in \mathcal{S}_{a(i)}^t, i \in \mathcal{K} \tag{3.13}$$

$$\sum_{s \in \mathcal{S}_{a(i)}^t} y_{as}^t \geq x_{ai}^t \qquad \forall a \in \mathcal{A}_{\mathcal{T}} \cup \mathcal{H}_{\mathcal{T}}, t \in \mathcal{T} \tag{3.14}$$

$$y_{as}^t \in \{0,1\} \qquad \forall a \in \mathcal{A}_{\mathcal{T}} \cup \mathcal{H}_{\mathcal{T}}, t \in \mathcal{T}, s \in \mathcal{S} \tag{3.15}$$

$$y_s \in \{0,1\} \qquad \forall s \in \mathcal{S} \tag{3.16}$$

$$\tag{3.17}$$

The objective function (3.11) minimizes the total number of platoons. Constraints (3.12) make sure that y_s is forced to one if trucks in s form a platoon together at any segment of their routes. Constraints (3.13) ensure that trucks in any s can be together in a platoon on a certain arc only if they all traverse that arc at the same time as determined by the first MIP. Constraints (3.14) ensure that we satisfy the solution of phase 1. Constraints (3.15) and (3.16) specify the domains of the variables.

Note that the stage 2 approach will find the solution with the lowest possible inconvenience given a stage 1 solution. When there are multiple stage 1 solutions, one of them could lead to a stage 2 solution with lowest possible inconvenience. This would happen when when there are multiple shortest paths with exactly the same length in the underlying graph. In practice, it is unlikely that there will be such equal-length paths. In theory, one can assume without loss of generality that all shortest paths in a graph are unique since ties may be broken by the addition of tiny random variables to arc lengths (Bodwin, 2019).

3.5 Special Cases: Platoon Pair Routing Problems

In this section, we look at special cases of the PRP-TW in which a truck can be part of at most one platoon per trip (M = 1) and platoons have a size of two (N = 2). We call this the *platoon pair routing problem with time windows (PPRP-TW).* Given all possible truck platoon pairs and their respective costs, we can model this problem as a general matching problem. These special cases provide us with insights and building blocks to develop heuristics for the PRP-TW.

Let $\mathcal{G}_{\mathcal{P}}$ be the *platoon pair graph* in which each node represents a truck in $\mathcal{K}$. In case two trucks $i, j \in \mathcal{K}$ can beneficially form a platoon, then the weight of the edge (i, j) represents the corresponding platoon costs L_{ij}. If a platoon with $i, j \in \mathcal{K}$ is not feasible or beneficial, then L_{ij} is the sum of the two shortest paths between the respective origins and destinations of the two trucks. Therefore, platoon pair graph $\mathcal{G}_{\mathcal{P}}$ is a complete graph. The problem to minimize the total system costs uses the objective $\min \sum_{i,j} L_{ij} x_{ij}$ with binary variables x_{ij}. To ensure that every truck is matched with a partner or travels alone, we include the constraints $\sum_i x_{ij} \geq 1 \, \forall j \in \mathcal{K}$. Therefore, to create platoon pair graph $\mathcal{G}_{\mathcal{P}}$, we need to solve a sub-problem to find costs L_{ij} for all $i, j \in \mathcal{K}$. Here, we consider all travel costs proportional to the travel distance. For readability, we ignore the multiplier between distances and costs in the remainder of this section.

Theorem 1. *An optimal solution to the PPRP-TW can be obtained in* $\mathcal{O}\big(|\mathcal{K}|^2|\mathcal{V}|^2(|\mathcal{V}| + |\mathcal{A}|log|\mathcal{V}|) + |\mathcal{K}|^3\big)$

Proof. Consider a single pair $i, j \in \mathcal{K}$. Consider an arbitrary pair of nodes $u, v \in \mathcal{V}$ to be the meeting point and split point. We can easily determine the costs of this platoon as

$$L_{ij}(u, v) = \sum_{k=1,2} d(o_k, u) + 2 \cdot \rho \cdot d(u, v) + \sum_{k=1,2} d(v, d_k)$$

In the worst case, finding the least-cost time-feasible platoon entails finding all shortest paths between the origins and meeting point u, the meeting point u and the split point v, and the split point v and the destinations. Each shortest path can be found in $\mathcal{O}(|\mathcal{V}| + |\mathcal{A}|log|\mathcal{V}|)$ (Dantzig, 1960). Doing this for all $|\mathcal{V}|^2$ pairs and compute the minimum costs L_{ij} therefore requires $\mathcal{O}\big(|\mathcal{V}|^2(|\mathcal{V}| + |\mathcal{A}|log|\mathcal{V}|)\big)$. We then compute the L_{ij} for all pairs $i, j \in \mathcal{K}$. This can be achieved in $\mathcal{O}\big(|\mathcal{K}|^2|\mathcal{V}|^2(|\mathcal{V}| + |\mathcal{A}|log|\mathcal{V}|)\big)$. With this, we now have platoon pair graph $\mathcal{G}_{\mathcal{P}}$. The final step to determining the total costs is finding the minimum weight matching on platoon pair graph $\mathcal{G}_{\mathcal{P}}$, which is a complete graph with $|\mathcal{K}|$ nodes.This can be accomplished in $\mathcal{O}(|\mathcal{K}|^3)$ (Gabow, 1990). The overall complexity is therefore $\mathcal{O}\big(|\mathcal{K}|^2|\mathcal{V}|^2(|\mathcal{V}| + |\mathcal{A}|log|\mathcal{V}|) + |\mathcal{K}|^3\big)$. □

Next, we focus on a relaxed version of the PPRP-TW in which the time windows are not binding. We call this the *platoon pair routing problem (PPRP).* The solution to this problem without time windows is a lower bound to the problem with time windows. In practice, we expect that the optimal solutions of this relaxed problem to usually also be time feasible as they are often associated with small detours.

Therefore, the insights we gain from analyzing the PPRP allow us to reduce complexity for cases in which the time windows are not very restrictive thereby speeding up computations and reducing run times for practical cases with time windows.

3.5.1 PPRP

Recall from Section 3.3 that the costs of traveling an edge a between nodes (u, v) alone is c_{uv} and the costs of traveling in a platoon is ρc_{uv} for each truck. For a pair of trucks $i, j \in \mathcal{K}$, we can transform this problem into a shortest path problem that aims to find a single least-costs path between a source and the sink in a transformed graph $\mathcal{G}_{\mathcal{E}} = (\mathcal{V}_{\mathcal{E}}, \mathcal{A}_{\mathcal{E}})$. We build the transformed graph by explicitly modeling the following three parts of a platoon routing solution.

1. the first legs of the trucks from their origins to the meeting point,
2. the joint platooning part
3. the last legs of the trucks to their destinations from the split point.

To model (1), we add a source node S to the original graph $\mathcal{G} = (\mathcal{V}, \mathcal{A})$. For each node $v \in \mathcal{V}$ that is a feasible meeting point based on Property 1, we add an edge connecting S and v. The weight of this edge is the sum of the costs for the two trucks to travel from their origins to meeting point v, i.e., $d_{\mathcal{E}}(S, v) = \sum_{k=1,2} d(o_k, v)$. To model (2), we adjust the weights of the edges $(u, v) \in \mathcal{A}$ of the original graph $\mathcal{G}_{\mathcal{E}}$ to account for the fuel consumption factor, i.e., $d_{\mathcal{E}}(u, v) = 2 \cdot \rho \cdot d(u, v)$. To model (3), we add a sink node T to the original graph $\mathcal{G} = (\mathcal{V}, \mathcal{A})$. For each node $v \in \mathcal{V}$ that is a feasible split point based on Property 1, we add an edge connecting v and T. The weight of this edge is the sum of the costs for the two trucks to travel from split point v to their destinations, i.e., $d_{\mathcal{E}}(v, T) = \sum_{k=1,2} d(v, d_k)$.

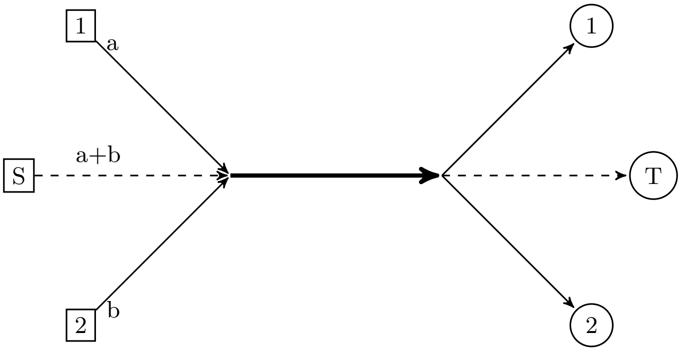


Figure 3.1: Transforming two paths into a single path

Proposition 1. *PPRP subproblem is equivalent to the shortest path problem in the following sense: any feasible solution to one problem can be transformed to a feasible solution of the other problem while attaining the same objective value.*

Proof. The proposition follows from the fact that

$$L(m,s) = \sum_k d(o_k,m) + 2 \cdot \rho \cdot d(m,s) + \sum_k d(s,d_k) = d_{\mathcal{E}}(S,T).$$

By definition, the distance $d_{\mathcal{E}}(S,T)$ is established by a shortest path in $\mathcal{G}_{\mathcal{E}}$. The first edge in that path (S,m) establishes the meeting point $m \in \mathcal{V}$ and the last edge (s,T) in that path establishes the split point $s \in \mathcal{V}$. □

In the following theorem, we establish the complexity of the PPRP.

Theorem 2. *An optimal solution to the PPRP can be obtained in* $\mathcal{O}\big(|\mathcal{V}||\mathcal{K}|^2(|\mathcal{V}|+|\mathcal{A}|log|\mathcal{V}|)+|\mathcal{K}|^3)\big)$

Proof. Consider a single pair $i,j \in \mathcal{K}$. Adding source S and sink T can be done in constant time. Modeling (1) requires us to add an edge while computing its weight, which we do by finding the shortest paths in $\mathcal{O}(|\mathcal{V}| + |\mathcal{A}|log|\mathcal{V}|)$. In the worst case, this needs to be done for every $v \in \mathcal{V}$ and this takes $\mathcal{O}\big(|\mathcal{V}|(|\mathcal{V}| + \mathcal{A}log|\mathcal{V}|)\big)$. Modeling (2) entails going over each arc $a \in \mathcal{A}$ of the graph G to modify its weight which takes $\mathcal{O}(|\mathcal{A}|)$. Finally, modeling (3) has the same complexity of modeling (1). Therefore the total time complexity to build transformed graph $\mathcal{G}_{\mathcal{E}}$ for a pair $i,j \in \mathcal{K}$ is $\mathcal{O}\big(|\mathcal{V}|(|\mathcal{V}| + |\mathcal{A}|log|\mathcal{V}|)\big)$. Then, we need to find a single shortest path between S and T on transformed graph $\mathcal{G}_{\mathcal{E}}$, which has $(|\mathcal{V}| + 2)$ nodes and $(|\mathcal{A}| + 2|\mathcal{V}|)$ edges. This can therefore be done in $\mathcal{O}(|\mathcal{V}| + (|\mathcal{A}| + |\mathcal{V}|)log|\mathcal{V}|)$. Hence the total time complexity to find the costs L_{ij} for $i,j \in \mathcal{K}$ and therefore build platoon pair graph $\mathcal{G}_{\mathcal{P}}$ is $\mathcal{O}\big(|\mathcal{V}|(|\mathcal{V}| + |\mathcal{A}|log|\mathcal{V}|)\big)$. As before, we can find the minimum weight matching in $\mathcal{O}(|\mathcal{K}|^3)$ making the overall complexity $\mathcal{O}\big(|\mathcal{V}||\mathcal{K}|^2(|\mathcal{V}| + |\mathcal{A}|log|\mathcal{V}|) + |\mathcal{K}|^3)\big)$. □

There is a factor $|\mathcal{V}|$ difference in the complexity of the subproblems of the PPRP and the PPRP-TW. This is because we only iterate over every node $u \in \mathcal{V}$ for the PPRP, as opposed to iterating over every node *pair* $u,v \in \mathcal{V}$ for the PPRP-TW.

We now outline how we can use the PPRP subproblem solution method to solve the PPRP-TW. Since the PPRP subproblem solution is a lower bound to the PPRP-TW subproblem, we do not need to solve the PPRP-TW subproblem for truck pairs $i,j \in \mathcal{K}$ that do not have a beneficial PPRP subproblem solution. For those that do, we include them in the platoon pair graph $\mathcal{G}_{\mathcal{P}}$ if they are time-feasible. Only for those pairs that are not time-feasible, we solve the the PPRP-TW subproblem using the MIP from Section 4 (note that we only need

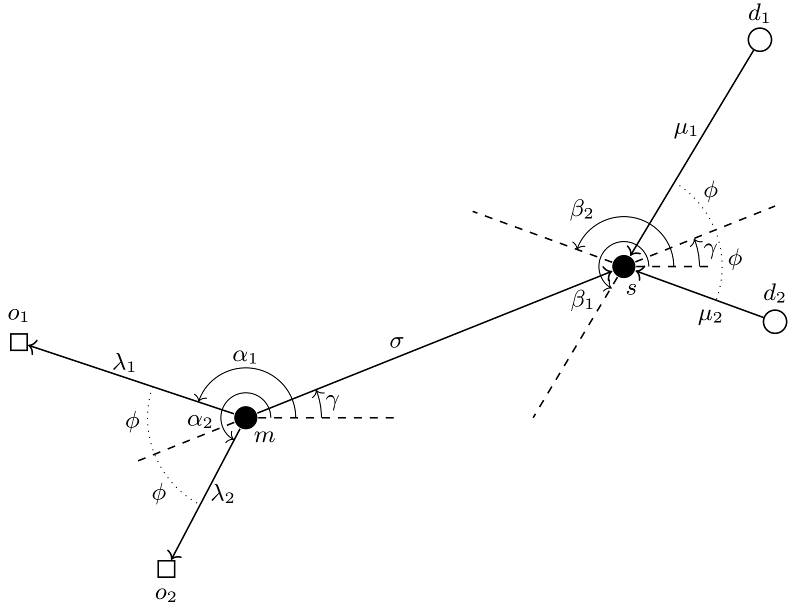


Figure 3.2: Platooning distance optimization in $\mathbb{R}^2$

phase 1). We can then find the minimum weight matching as earlier. Note that in practice, we can pre-compute or use parallel computing for the different steps to build the platoon pair graph $\mathcal{G}_{\mathcal{P}}$.

3.5.2 PPRP on the Euclidean Plane

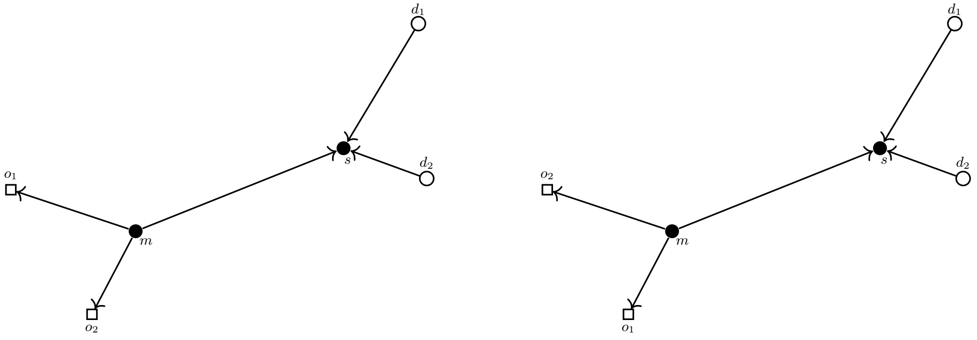
In the Euclidean plane, finding the costs of both trucks taking their respective shortest paths is an easy and straightforward exercise. Finding the costs of platooning, on the other hand, requires us to determine the meeting point m and split point s that minimize the platoon costs. Once we have these points, the travel costs may be determined as follows:

$$L(m,s) = \sum_k \|o_k - m\|_2 + 2\rho\|m - s\|_2 + \sum_k \|s - d_k\|_2 \tag{3.18}$$

where we assume that $s \neq m$. Observe that in the case when $s = m$, we arrive at

$$L(m,m) = \sum_k \Big\{ \|o_k - m\|_2 + \|m - d_k\|_2 \Big\} \geq \sum_k \|o_k - d_k\|_2,$$

which implies that platooning is not beneficial. Also when $\rho = 1$, platooning will never result in savings, so we do not consider this case. Another case in which platooning is not



(a) $\delta_1 = +1$ and $\delta_2 = -1$ **(b)** $\delta_1 = -1$ and $\delta_2 = -1$

Figure 3.3: Example of changed positions of o_1 and o_2 with changing $\delta_k, k = 1, 2$

beneficial is when $\|o_1 - o_2\|_2 + \|d_1 - d_2\|_2 \geq \sum_k \|o_k - d_k\|_2$, as the total distance with platooning will then always be larger than the direct truck distances.

We now describe how we find m and s. Figure 3.2 shows the notation that we use. In addition to these, we introduce $\delta_k \in \{-1, 1\}$ which specify the orientation of the origins and destinations with respect to each other. For instance, in Figure 3.2, we have $\delta_1 = +1$ and $\delta_2 = -1$. A sign change of δ_1 corresponds with a swap of the two origins and a sign change of δ_2 represents a swap in the destinations. An example is shown in Figure 3.3, where δ_1 being -1 in Figure 3.3b corresponds to a swap in the origins as compared to Figure 3.3a where $\delta_1 = +1$. Also, define unit vector $u_\delta = (\cos(\gamma + \pi + \delta\phi), \sin(\gamma + \pi + \delta\phi))^T$ for $\delta \in \{-1, +1\}$, and $v = (\cos\gamma, \sin\gamma)^T$. The proof of Theorem 3 is provided in Appendix 3.10.1.

Theorem 3. *The meeting point m and the separation point s leading to a unique minimum total costs $L(m, s)$ can be computed as follows. We write $\lambda_k = \|o_k - m\|_2$, $\mu_k = \|s - d_k\|_2$, and $\sigma = \|s - m\|_2$, so that*

$$L(m, s) = \sum_k \lambda_k + 2\rho\sigma + \sum_k \mu_k, \tag{3.19}$$

$$m = o_1 - \lambda_1 u_{-\delta_1} = o_2 - \lambda_2 u_{+\delta_1}, \tag{3.20}$$

$$s = d_1 + \mu_1 u_{-\delta_2} = d_2 + \mu_2 u_{+\delta_2}, \tag{3.21}$$

where λ_k and μ_k are given by

$$\lambda_1 = -r_o \frac{\sin(\varphi_o - \gamma - \delta_1\phi)}{\sin 2\delta_1\phi}, \tag{3.22}$$

$$\lambda_2 = -r_o \frac{\sin(\varphi_o - \gamma + \delta_1\phi)}{\sin 2\delta_1\phi}, \tag{3.23}$$

$$\mu_1 = r_d \frac{\sin(\varphi_d - \gamma - \delta_2 \phi)}{\sin 2\delta_2 \phi}, \tag{3.24}$$

$$\mu_2 = r_d \frac{\sin(\varphi_d - \gamma + \delta_2 \phi)}{\sin 2\delta_2 \phi}, \tag{3.25}$$

and

$$\sigma = r_1 \cos(\varphi_1 - \gamma) - (\lambda_1 + \mu_1) \cos \phi. \tag{3.26}$$

These parameters are defined by the initial data $o_2 - o_1 = (r_o \cos \varphi_o, r_o \sin \varphi_o)^T$, $d_2 - d_1 = (r_d \cos \varphi_d, r_d \sin \varphi_d)^T$, *and* $d_1 - o_1 = (r_1 \cos \varphi_1, r_1 \sin \varphi_1)^T$, *and the angle* γ. *The latter is given by*

$$\gamma = \arctan \frac{A}{B} + \delta_3 \pi, \tag{3.27}$$

where $\delta_3 \in \{0, 1\}$ *and* A *and* B *are defined by the initial data as follows:*

$$A = 2r_1 \cos \phi \sin \varphi_1 + r_d \sin(\varphi_d - \delta_2 \phi) - r_o \sin(\varphi_o - \delta_1 \phi), \tag{3.28}$$

$$B = 2r_1 \cos \phi \cos \varphi_1 + r_d \cos(\varphi_d - \delta_2 \phi) - r_o \cos(\varphi_o - \delta_1 \phi). \tag{3.29}$$

The angle ϕ *is given by* $2\phi = |\alpha_1 - \alpha_2| = |\beta_1 - \beta_2|$. *We may now compute* m *and* s *from the initial data given by (3.20) and (3.21).*

Next, the following theorem confirms that in the case of the Euclidean Plane, the meeting point m and the separation point s are in the convex hull of the origins and the destinations. We define the convex hull of a set of points as

$$\mathrm{C}onv(\{x_i\}) = \left\{ \sum_i a_i x_i \mid \sum_i a_i = 1 \right\}.$$

Theorem 4. *The meeting point* m *and the separation point* s, *as defined in Theorem 3 are in the convex hull of the origins and the destinations, i.e.* $s, m \in \mathrm{C}onv(\{o_1, o_2, d_1, d_2\})$. *In particular, convex combinations are given, when* $\delta_1 \delta_2 = -1$, *by*

$$m = \frac{\lambda_2 \theta}{w_{11}} o_1 + \frac{\lambda_1(\mu_1 + \theta)}{w_{11}} o_2 + \frac{\lambda_1 \lambda_2}{w_{11}} d_1, \tag{3.30}$$

$$s = \frac{\mu_1 \mu_2}{z_{22}} o_2 + \frac{\mu_2(\lambda_2 + \theta)}{z_{22}} d_1 + \frac{\mu_1 \theta}{z_{22}} d_2, \tag{3.31}$$

and, when when $\delta_1 \delta_2 = +1$, *by*

$$m = \frac{\lambda_2(\theta + \mu_1)}{w_{21}} o_1 + \frac{\lambda_1 \theta}{w_{21}} o_2 + \frac{\lambda_1 \lambda_2}{w_{21}} d_1, \tag{3.32}$$

$$s = \frac{\mu_1 \mu_2}{z_{21}} o_2 + \frac{\mu_2 \theta}{z_{21}} d_1 + \frac{\mu_1(\lambda_2 + \theta)}{z_{21}} d_2, \tag{3.33}$$

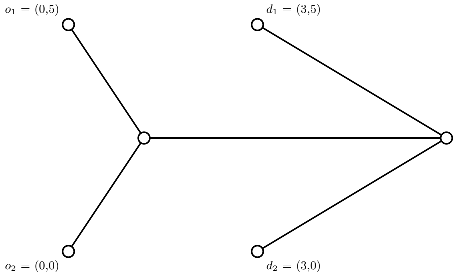


Figure 3.4: Example of a sparse network on which the trucks would automatically platoon

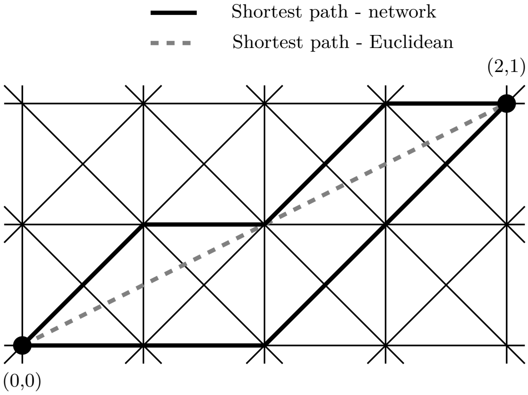


Figure 3.5: Shortest paths on the network and Euclidean plane

where

$$\theta = \frac{\sigma}{2\rho},$$

$$w_{ij} = \lambda_i \mu_j + \lambda_1 \lambda_2 + \lambda_1 \theta + \lambda_2 \theta,$$

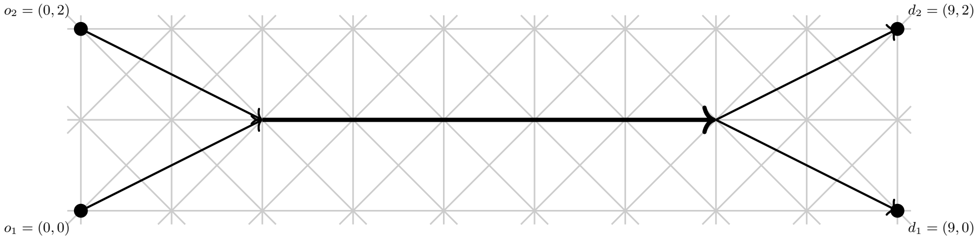
$$z_{ij} = \lambda_i \mu_j + \mu_1 \mu_2 + \mu_1 \theta + \mu_2 \theta,$$

for $i, j \in \{1, 2\}$.

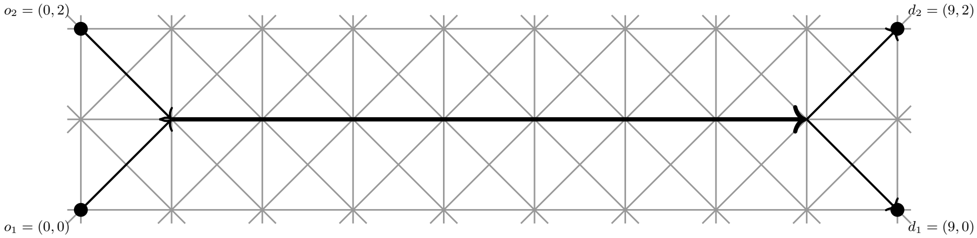
The proof of Theorem 4 is given in Appendix 3.10.1.

We now investigate how the solution of the PPRP on the Euclidean plane translates to the PPRP. This would hinge on the density of the network underlying the PPRP. For instance, the Euclidean solution could indicate that the truck pair cannot feasibly form a platoon but they might be able to on a sparse network. For example, given the network in Figure 3.4, the only possible paths would automatically create a platoon.

On the other hand, in a dense network one would expect the Euclidean solution being a good approximation for the network solution. However, this is not necessarily the case.



(a) Feasible Euclidean plane solution



(b) Infeasible network solution

Figure 3.6: Example of the optimal platoon for a truck pair being feasible on the Euclidean plane but being infeasible on a dense network; $\rho = \frac{2}{\sqrt{5}}$

Consider the example in Figure 3.5 where δ defines the grid density. In this grid, the lengths of shortest path between the points (0,0) and (2,1) can be calculated as $1 + \sqrt{2}$ while the corresponding value on the Euclidean plane is $\sqrt{5}$. Note that this shortest path on the grid is independent of grid density δ. This shows us that making the grid denser does not influence the ratio of the distances in the network and the Euclidean plane.

We use this to build up an example we show in Figure 3.6. Let the fuel consumption factor $\rho = \frac{2}{\sqrt{5}}$. Here, we can calculate the costs of platooning in the Euclidean plane as approximately 17.88 while the corresponding costs on a the network are 18.18. Comparing these figures to the direct trucking costs of 18 indicates that a platoon is feasible on the Euclidean plane but not on the dense network.

Therefore, the theoretical translation of the Euclidean solution to the network case is not straightforward. We investigate this further in our numerical experiments on a practical case in Section 3.7.

Next, we evaluate if a similar convexity result as in Theorem 4 holds true in the case of a network graph. In a graph setting, the notion of geodesic convexity has been prominently used (Farber & Jamison, 1987). In a graph $\mathcal{G} = (\mathcal{V}, \mathcal{A})$, a set of nodes $\mathcal{C} \subseteq \mathcal{V}$ is geodesically convex if $\mathcal{C}$ contains all nodes in the shortest path between any $u, v \in \mathcal{C}$. The geodesic convex hull of $\mathcal{C}$ is then the smallest geodesically convex set that contains $\mathcal{C}$.

In Figure 3.7, we present an example in which the split point is not contained in the geodesic convex hull of the origins and destinations $conv_g(o, d_1, d_2) = \{o, d_1, d_2\}$. We can

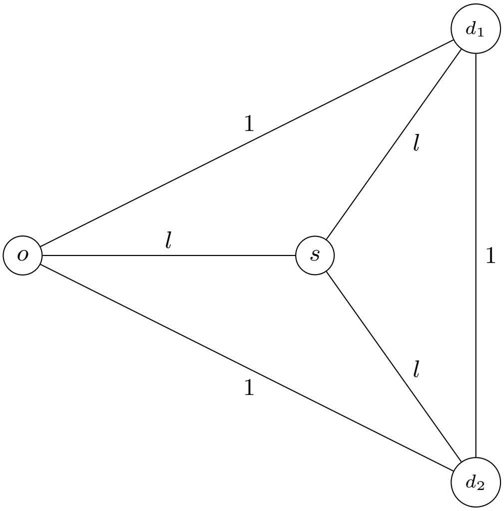


Figure 3.7: Counter example in case of networks

easily calculate the value of l to be $\frac{1}{3}\sqrt{3}$. We have two trucks $k \in \{1,2\}$ traveling from the same origin o to their destinations d_1 and d_2. Let $L(o,x)$ denote the costs of both trucks driving to their destinations splitting up at node x. Here, x can either o, s, and d_k. We can calculate the costs of each -

- $L(o,o) = \sum_k d_{od_k} = 2$
- $L(o,s) = 2 \cdot \rho \cdot d_{os} + \sum_k d_{sd_k} = \frac{2}{3}\sqrt{3}(1+\rho)$
- $L(o,d_k) = 2 \cdot \rho \cdot d_{od_k} + d_{d_1 d_2} = 2\rho + 1$

Since $\rho > 1/2$ for a 2-truck platoon (see Section 3.3), we will always have $L(o,d_k) > L(o,o)$ so the trucks would never choose this route to minimize costs. For $L(o,s) < L(o,o)$, we need $\frac{2}{3}\sqrt{(}3)(1+\rho) < 2$ or $\rho < \sqrt{3} - 1 \approx 0.73$ so for any $0.5 < \rho < 0.73$, the trucks will split up at $s \notin conv_g(o, d_1, d_2)$.

3.6 Heuristics

In this section, we present a number of heuristics for the PRP-TW based on the special cases discussed in Section 3.5. The general idea is to find a 2-truck platooning solution first and then use an *improvement* procedure to potentially find additional (larger) platoons.

3.6.1 Shortest path heuristic

The shortest-path heuristic (SPH) creates a set of 2-truck platoons. As described in Section 3.5, we can formulate the associated truck pair routing problem as a general matching problem on a platoon pair graph $\mathcal{G}_{\mathcal{P}}$ to minimize total costs. To determine the costs of a platoon between truck pair $i, j \in \mathcal{K}$ we use a heuristic approach based on the procedure described in Section 3.5.1.

As a first step, we use the shortest path approach to find the best routes for every 2-truck pair of trucks $i, j \in K$ that satisfy Property 2 to form a platoon. This involves finding the appropriate meet and split points. If the shortest path algorithm does not find a feasible platoon, we do not include this pair in the matching. If a beneficial platoon is found, we test for time feasibility. That is, we check if the trucks can both reach their destinations in time when meeting as early as possible. If the platoon is time feasible we include these costs in the platoon pair graph $\mathcal{G}_{\mathcal{P}}$. If the optimal spatial platoon route is not beneficial or time feasible, we assume the trucks can not form a platoon. To denote this, we set the costs of the associated pair to be the sum of their direct distances. Note that this is a heuristic for the time constrained two truck case as we ignore the possibility that there could exist a time feasible platooning route that is different from the beneficial route that ignored time windows.

3.6.2 Euclidean heuristic

As in the previous section, we construct a general matching problem to create 2-truck platoons. In the Euclidean heuristic (EUH), we apply the analytical results of Section 3.5.2 to determine possible platoon pairs. In particular, we use expressions (3.30) - (3.33) to find the potential meeting and split points on the Euclidean plane for each pair of trucks $i, j \in \mathcal{K}$. We then 'round' these Euclidean coordinates to the closest discrete nodes on the network $\mathcal{G}$. That is, for both the meet and split point, we find the nearest node on the network in terms of Euclidean distance. If this platoon route is both beneficial and time-feasible, we include these platoon costs for truck pair i, j in the platoon pair graph $\mathcal{G}_{\mathcal{P}}$ and if not, we use the sum of their direct distances.

3.6.3 Improvement procedure

The above approaches generate platooning solutions with 2-truck platoons. It may, however, be possible and beneficial to still create larger platoons by merging some of the trucks that drive alone to a platoon. Therefore, we run an improvement procedure that is inspired by the shortest path approach in Section 3.5.1.

For a given platoon solution, let $\mathcal{P}$ be the set of trucks that are part of a platoon, and $\mathcal{Q}$ be the set of trucks that are not part of a platoon. In the graph, we now modify the costs of traveling along the path of an existing platoon to capture the potential savings of joining that platoon. We do this by multiplying the weights of the edges along all these paths by ρ. Let the network with the modifications for all trucks $i \in \mathcal{P}$ be $\mathcal{G}'$.

We then route trucks in $\mathcal{Q}$ on $\mathcal{G}'$ and check if there are platoon possibilities. For each truck $j \in \mathcal{Q}$, we check if its least cost route in the modified network $\mathcal{G}'$ overlaps with existing platoon routes and evaluate for time feasibility. In case of time feasibility, truck j can join a platoon in $\mathcal{P}$ to decrease total travel costs. Note that, Property 3 implies that we do not need to explicitly check for the platoon size constraint N for $N \geq 3$.

We can apply this improvement procedure on both SPH and EUH giving us two additional heuristics which we call SPH$^+$ and EUH$^+$.

3.7 Numerical experiments

In this section, we describe and report the results of a set of computational experiments on different instances. We determine the benefits of different platooning configurations by varying the maximum number of trucks per platoon and the number of platoons per truck trip. As we mentioned in Section 3.1, platoons of three trucks in practice already cause a lot more disruption to traffic than 2-truck platoons. Keeping this in mind, we restrict ourselves to arrangements in which a maximum of three trucks are allowed in a platoon. Note that increasing the maximum allowed platoon size will not create more platoons as an implication of Property 3. In addition, the cost structure we use (see Section 3.3) would keep the total costs the same.

We then follow this up by assessing the performance of the different heuristics. Since the heuristics take advantage of structural properties of restricted cases, we use these results to provide more detailed insights. We also conduct certain sensitivity analyses to assess the effects of different parameters on the total platooning benefits. In the MIP formulation, we use a discretization parameter of 15 minutes. Tests show that this value provides a good balance between performance and computational efficiency (see Appendix 3.10.2). All results presented in this section have been averaged over five random truck trip instances and were implemented in Python 3.6.3 with Gurobi 7.0 as the IP solver on an Intel i7-6820HQ machine with 2.70Ghz processor.

3.7.1 Description of the instances

We generate instances on a network that represents the Dutch highway system with 20 cities represented by nodes and 45 road segments represented by edges. Figure 3.8 shows

Figure 3.8: Representation of the Dutch highway network

the network. The weights of the edges represent the travel costs between two cities and are proportional to the real distances (Google maps). In particular, we generate three sets of trip instances with different distributions of origins and destinations. In the first set of instances, UNIFORM, each node in the network is equally likely to be an origin and a destination for a truck. The next set of instances is inspired by our collaboration with the Port of Rotterdam. Here, all trips either start (ONEORIG) or end at one node (ONEDEST) in the network, i.e., the node that represents Rotterdam.

For all instances, we generate the earliest start times randomly in the one hour window between 07.00 and 08.00, which is inspired by our collaboration with various transportation service providers that operate between the Port of Rotterdam and the hinterland. We calculate their latest arrival times by adding the available flexibility to their shortest path times or $l_k = a_k + t_{o_k d_k} + f_k$ for truck $k \in \mathcal{K}$. We use a fuel consumption factor ρ of 0.90 which corresponds to 10% savings of driving in a platoon (McAuliffe et al., 2018). To facilitate easier interpretation of the results, we use a constant flexibility of 30 minutes for all trucks.

Max. trucks per platoon Platoons per trip	3 ∞	2 ∞	2 1
UNIFORM			
Fuel savings (%)	3.5	3.3	3.3
Platoon km (%)	37.3	36.3	35.6
Trucks in platoon (%)	60.0	56.7	53.3
Platoons with detour (%)	19.6	20.9	8.8
Detour distance (%)	2.5	3.0	2.1
ONEORIG			
Fuel savings (%)	9.5	8.8	8.8
Platoon km (%)	95.2	89.1	88.8
Trucks in platoon (%)	99.3	98.0	94.7
Platoons with detour (%)	1.0	2.8	0.7
Detour distance (%)	0.1	1.8	1.1
ONEDEST			
Fuel savings (%)	8.4	7.6	7.5
Platoon km (%)	83.6	76.7	76.4
Trucks in platoon (%)	88.0	86.7	84.0
Platoons with detour (%)	1.8	3.0	3.1
Detour distance (%)	0.1	3.5	3.3

Table 3.1: Platooning solution characteristics; 30 trucks; averaged over five random instances; $\rho = 0.9$

3.7.2 Impact of constraints

Here, we consider the impact of the different problem constraints on the solutions and run times. In particular, we look at the maximum number of trucks ($N \geq 2$) per platoon and the number of platoons per trip (one or unrestricted - $M \in \{1, \infty\}$). Recall that we denote each setting with the tuple (N, M). Therefore, we determine optimal platoons for a number of settings. For $(3, \infty)$ and $(2, \infty)$, we use the MIP from Section 3.4. For $(2, 1)$, we use the procedure from Section 3.5.1.

In Table 3.1, we report the percentage fuel savings, the total platooning kilometers as a percentage of the total direct distance, the proportion of trucks that are part of at least one platoon, the percentage of platoons with at least one truck making a detour, and the total detour distance expressed as a percentage of the total direct distance for the trucks with a detour. We calculate the percentage fuel savings as follows. Let Z^0 be the total costs if all trucks took their shortest paths and Z^* be the total costs with platooning. The percentage fuel savings are then

$$\text{Percentage savings} = 100 \cdot \frac{Z^0 - Z^*}{Z^0}$$

As expected, less constrained $(3, \infty)$ allows for more platoon savings than the more constrained 2-truck cases. However, we see that the differences are very small, for instance, a 0.2 percentage point difference between $(3, \infty)$ and $(2, \infty)$ in UNIFORM. This also applies to the percentage platoon kilometers (1 p.p.) and also the percentage of trucks in a platoon. There is no difference between the 2-truck cases with both $(2, \infty)$ and $(2, 1)$ having fuel savings of 3.3%. This suggests that the value of allowing multiple platoons per trip is low.

Moreover, we see that there are higher savings in ONEORIG and ONEDEST as compared to UNIFORM. ONEORIG results in 9.5% savings as compared to 3.5% for UNIFORM. The reason is that it is much easier for trucks to find platoon partners when they are all starting from the same origin or heading to the same destination. We see that almost all trucks are part of a platoon in most cases. Looking at the different constraints across the instances, it appears that the value of having fewer constraints (i.e., (3,∞)) is greater in ONEORIG and ONEDEST. One potential explanation is that it is easier to exploit the extra flexibility in these instances because the trips of all trucks are spatially similar.

Moreover, we see higher savings (and more platoon km) in ONEORIG than in ONEDEST. This is somewhat surprising as both instances have a very similar route structure. The reason for this difference is related to the distribution of the time windows. Recall that the earliest departure times of all trucks are uniformly distributed between 7.00 and 8.00. This means that all trucks leave the origin around the same time but arrive at their destination at different times depending on their travel distances. As a result, the variation in arrival times is larger than the variation in departure times, which means that trucks can more easily be matched into platoons at their origins that at their destinations.

We now look at the detour characteristics. The percentage of platoons with a truck making a detour in UNIFORM is the highest for $(2, \infty)$ at 20.9% compared to the 19.6% for $(3, \infty)$ and 8.8% for $(2, 1)$. This is due to the difference in freedom trucks have to join platoons. In $(3, \infty)$, trucks have more freedom and can find platoons without longer detours. In addition, the costs of a detour prohibit trucks from significantly deviating from their shortest paths. Therefore, they tend to find platoon partners closer to the vicinity of their direct routes. This would also hold true when trucks are spatially clustered like in ONEORIG and ONEDEST, where only 1% and 1.8% of the trucks make a detour.

Note that although the additional fuel savings are small, the run times are much larger in the cases that allow for multiple platoons per truck. This is evident from Table 3.2 in which we report the average, maximum, and minimum run times of each setting for all sets of instances. For UNIFORM, $(3, \infty)$ requires 516 seconds on average while $(2, \infty)$ and $(2, 1)$ require 316 seconds and 280 seconds respectively.

Among the different instances, ONEORIG mostly has the largest run times. This is because of the higher number of possible platooning opportunities as a result of the trucks starting at the same node with less variability in their departure times than ONEDEST like we discussed. However, the run times of $(2, 1)$ are unexpectedly high for ONEDEST. This is again due to the higher variability in the arrival times of the trucks at the common

Max. trucks per platoon	3	2	2
Platoons per trip	∞	∞	1
UNIFORM			
Average	516	316	280
Maximum	662	389	345
Minimum	420	248	209
ONEORIG			
Average	2453	773	416
Maximum	4951	850	627
Minimum	1196	633	266
ONEDEST			
Average	1172	576	846
Maximum	2160	768	1022
Minimum	538	444	635

Table 3.2: Run times in seconds for different instances; 30 trucks; averaged over five random instances; $\rho = 0.9$

destination. Because all trucks are heading to the same destination, there are many routes in close spatial proximity. As a result, there will be many beneficial platoon pairs but because of the variability in time, they are likely to be time-infeasible. Recall from Section 3.5.1 that the MIP needs to be called for these pairs before finding the optimal matching, which adds to the run times.

3.7.3 Solution structure

The solution in which a truck can be part of multiple platoons along the route creates interdependencies between different platoons in time and space. To provide more insights into these interdependencies, we study the structure of the solution by looking at the larger platoon arrangements that have overlaps in the involved trucks.

To analyze these platoon arrangements, we create an undirected *truck connectivity graph* $\mathcal{P} = (\mathcal{K}', \mathcal{E})$. $\mathcal{K}'$ contains a node for each truck that is part of at least one platoon. Two nodes are connected by an edge $e \in \mathcal{E}$ if the associated trucks are in a platoon together. Each component in the truck connectivity graph represents a platoon arrangement. A component is a sub-graph in which every node is connected to every other node by a path. Two examples of platoon arrangements and their corresponding truck connectivity graphs are shown in Table 3.3. In the first platoon arrangement, trucks 1 and 2 are in a platoon together and are therefore connected in the truck connectivity graph. The following platoon arrangement has trucks 3,4,5 in a platoon together at first due to which they are all connected to each other in the corresponding truck connectivity graph. The platoon then loses truck 3 and truck 6 joins. Therefore, truck 6 is connected to trucks 4,5 in the truck connectivity graph but not to truck 3 since they are never in the same platoon together.

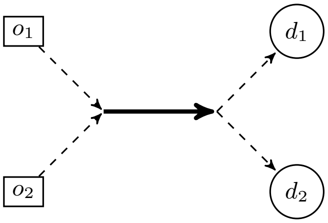
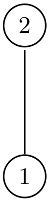
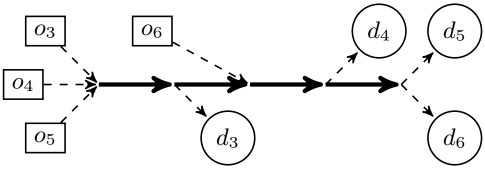
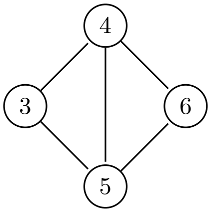
Platoon arrangement	Truck connectivity graph
	
	

Table 3.3: Examples of truck connectivity graphs

From the truck connectivity graph, we compute several statistics. The number of components provides more insight into the number of platoon arrangements in the solution. The size of these components is the number of trucks in their corresponding platoon arrangements. We also find the path between any two connected nodes in the truck connectivity graph to measure the separation between trucks. The separation indicates if two trucks are in a platoon together or if two trucks are linked by some common platoon partners and if so, how many. Therefore, the higher the separation is between any two trucks in a platoon arrangement, the higher the number of trucks there are in the arrangement, and the more frequently a truck joins or leaves a platoon in the arrangement.

Table 3.4 presents the number of arrangements, the average and largest arrangement sizes, and the largest separation. Note that the minimum component size is always 2. As expected, we see only components of size 2 in $(2, 1)$. Here, all platoons are independent. Comparing $(2, 1)$ and $(2, \infty)$ we see that the component sizes and the largest separation increases slightly when trucks are allowed to switch between different 2-truck platoons. The arrangement sizes and largest separation increase significantly for $(3, \infty)$. This suggest that trucks “piggyback” on existing 2-truck platoons close to their route. This is also the reason that we have fewer but larger arrangements in $(3, \infty)$. The higher number of trucks in these arrangements reiterates the requirement of the greater coordination efforts to plan these larger platoons.

For the different instances, we notice that the arrangement sizes are higher for ONEORIG and ONEDEST in $(3, \infty)$. In $(3, \infty)$, trucks have more freedom to join and leave platoons. The higher spatial proximity in ONEDEST and ONEORIG allows trucks to make more use of this greater freedom leading to larger platoon arrangements.

Max. trucks per platoon Platoons per trip	3 ∞	2 ∞	2 1
UNIFORM			
Number of arrangements	6.6	8.4	8.0
Average arrangement size	2.5	2.1	2
Largest arrangement size	4.8	2.2	2
Largest separation	2.6	1.2	1
ONEORIG			
Number of arrangement	5.6	14.4	14.2
Average arrangement size	3.6	2	2
Largest arrangement size	14.4	2.2	2
Largest separation	6.8	1.2	1
ONEDEST			
Number of arrangement	8.0	12.8	12.6
Average arrangement size	2.9	2	2
Largest arrangement size	8.2	2.3	2
Largest separation	4.4	1.8	1

Table 3.4: Truck connectivity graph characteristics; 30 trucks; averaged over five random instances; $\rho = 0.9$

3.7.4 Performance of the heuristics

Here, we assess the performance of the heuristics presented in Section 3.6 by comparing their results with the optimal values of the (3,∞) solution. SPH and EUH represent the basic 2-truck platooning heuristics and SPH$^+$ and EUH$^+$ the versions in which we apply the improvement procedure. Table 3.5 reports the optimality gaps and run times of these four heuristics.

Overall, we see that SPH$^+$ performs best with optimality gaps of less than 1%. Even without the improvement step, SPH performs well, i.e., with optimality gaps of less than 1.46%. This is in line with our earlier observation that optimal (2,1) solutions are not so much worse than the less constrained optimal (3, ∞) solutions. However, the run times of the heuristics are far lower than the run times of our exact methods as shown in Table 3.2.

EUH and EUH$^+$ show even smaller run times but with a lower performance with 2-3% optimality gaps. A possible reason for the lower performance is that it can be difficult to translate the Euclidean solutions to a network solution as discussed in Section 3.5.2. To provide some more insight into this ‘rounding’ step, we show an example with two trucks in Figure 3.9. The first truck needs to travel from from Groningen to Rotterdam and the second from Utrecht to Breda. Figure 3.9a shows the optimal network solution in which the trucks platoon between Utrecht and Rotterdam. Figure 3.9b shows the Euclidean plane solution and the resulting rounded network solution. Both the meet and split points are rounded to Utrecht which means that no platooning takes place.

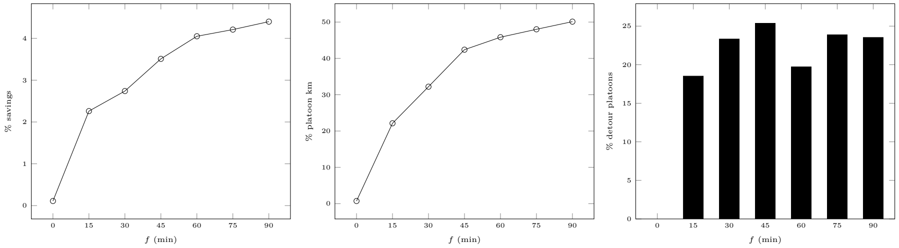
	SPH	SPH$^+$	EUH	EUH$^+$
UNIFORM				
Average (%)	0.34	0.15	2.42	2.09
Maximum (%)	0.77	0.24	3.52	3.52
Minimum (%)	0	0	1.59	1.08
# optimal	1	2	0	0
Run time (s)	1.79	1.81	0	0.01
ONEORIG				
Average (%)	0.79	0.55	2.10	1.97
Maximum (%)	0.95	0.90	2.20	2.06
Minimum (%)	0.59	0.32	2.05	1.90
# optimal	0	0	0	0
Run time (s)	1.83	1.84	0	0.01
ONEDEST				
Average (%)	1.31	0.25	2.23	2.03
Maximum (%)	1.46	0.81	2.41	2.27
Minimum (%)	1.18	0.12	2.12	1.87
# optimal	0	0	0	0
Run time (s)	1.75	1.77	0	0.01

Table 3.5: Optimality gaps and run times of heuristics; 30 trucks; averaged over five random instances; $\rho = 0.9$

(a) Optimal 2-truck solution

(b) Euclidean 2-truck solution and rounded network solution

Figure 3.9: Example of optimal vs Euclidean solution



(a) Variation in % savings **(b)** Variation in % platoon km **(c)** Variation in % detour platoons

Figure 3.10: Effects of varying f; 30 trucks; averaged over five random instances; $\rho = 0.9$

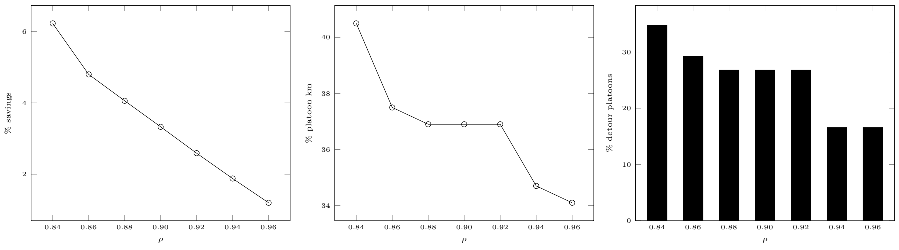
3.7.5 Impact of time flexibility, fuel consumption factor, and truck density

We now study the impact of the truck density (number of s) and their flexibility f on the performance of the system. In addition, we also look at the effect of the fuel consumption factor ρ. For these experiments, we use the best performing heuristic SPH$^+$. We run these sensitivity analyses using the UNIFORM instances.

We vary flexibility f between 0 and 90 minutes with increments of 15 minutes for instances with 30 trucks. Figure 3.10 shows the fuel savings, the platoon kilometers relative to the setting without platoons, and the percentage of platoons with a truck making a detour. From Figures 3.10a and 3.10b, we see that both the fuel savings and the percentage platoon kilometer values increase with higher flexibility. Moreover, we see a diminishing increase at higher flexibility. We observe that allowing a flexibility of 15 minutes makes a significant difference as compared to having no flexibility at all. From a practical perspective, our results suggest that we would only need a relatively small amount of time flexibility to achieve benefits from platooning.

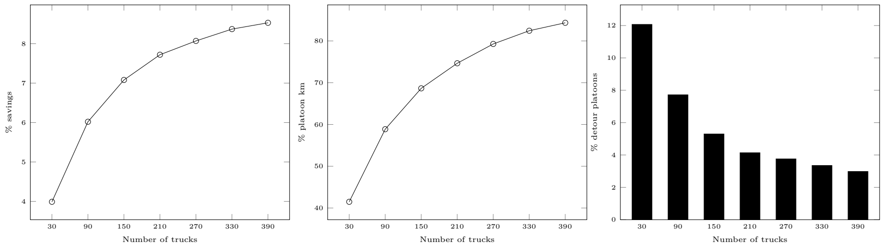
Interestingly, Figure 3.10c shows that the percentage of platoons in which a truck makes a detour is roughly the same for different values of flexibility. One explanation for this is that the detours are automatically minimized to maximize the platoon benefits. That is, long detours would offset fuel cost savings and thus render platoons non-beneficial. The experiments also show that the percentage detour distance also remains fairly constant with increasing flexibility.

In practice, the fuel consumption factor ρ depends on several factors like the surrounding traffic, terrain, or headway. In this experiment, we consider values between 0.84 and 0.96 in steps of 0.02. We again plot the percentage savings, the percentage platoon kilometers and the percentage of trucks in at least one platoon in Figure 3.11. We observe a roughly linear trend in the percentage savings from Figure 3.11a. Figures 3.11a, as expected, indicates that the platoon kilometers increase with higher fuel savings, i.e., lower ρ. However, the



(a) Variation in % savings **(b)** Variation in % platoon km **(c)** Variation in % detour platoons

Figure 3.11: Effects of varying ρ; 30 trucks; averaged over five random instances; flexibility = 30 min



(a) Variation in % savings **(b)** Variation in % platoon km **(c)** Variation in % detour platoons

Figure 3.12: Effects of varying the truck density; flexibility = 30 min; averaged over five random instances; $\rho = 0.9$

differences are relatively small. We see a similar trend in Figure 3.11c with the percentage of trucks making a detour. Trucks can make more detours when the platoon savings are higher since the savings offset the additional detour costs.

Next, we vary the number of trucks between 30 and 390 in steps of 60. In Figure 3.12, we plot the percentage savings, the percentage platooning kilometers and the percentage of platoons with at least one truck making a detour. Figures 3.12a and 3.12b again show a diminishing increase. As expected, the number of platoons increases with the number of trucks. Hence, equipping more trucks with platooning technology at the deployment stages would make a significant difference.

Not only is it more likely for trucks to form platoons with a higher truck density but they also need less detours to do so. Figure 3.12c shows that the percentage of trucks that make a detour to form platoons goes down with an increase in the number of trucks.

3.8 Concluding remarks

Platooning technology virtually connects trucks and helps save fuel and reduce associated emissions by reducing aerodynamic drag. In this chapter, we looked at the planning truck platoons by determining the paths and time schedules of s between their origins and destinations. In particular, we focused on a restricted case in which a truck can join at most one platoon and we only consider platoons of two trucks. We referred to this problem as the Platoon Pair Routing Problem (PPRP-TW and PPRP). We showed that this problem can be solved in polynomial time and provide several fast exact methods and heuristics. To evaluate the impact of restricting the possible platoons, we also present a novel MIP to solve the general platoon planning routing with time windows (PRP-TW).

To assess the impact of the restrictions and evaluate the heuristics, we ran a set of numerical experiments on instances based on the Dutch highway network. Our experiments showed that the restrictive setting with 2-truck platoons is associated with similar fuel savings as the less restricted settings. Moreover, it is computationally less challenging to create two truck platoons. Our heuristics also provide very good results. They consistently produced results within a percent of the optimum.

In this chapter, we focused on a static setting in which we plan the platoons in advance. A natural direction for further research is to consider dynamic trip announcements and travel time uncertainty.

3.9 Acknowledgements

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3.10 Appendices

3.10.1 Platooning on the Euclidean plane

We establish the proof of Theorem 3. Note that $L(m, s)$ as defined in (3.18) is differentiable whenever

$$(m, s) \in \mathcal{D} = \{(x, y) \in \mathbb{R}^2 \times \mathbb{R}^2 : x \neq y,\ o_k \neq x,\ y \neq d_k,\ k \in \{1, 2\}\}.$$

We will demonstrate that $L(m, s)$ is strictly convex, so that there exists a unique (m, s) for which $L(m, s)$ attains its minimum value. When $L(m, s)$ has a critical point in $\mathcal{D}$, then $L(m, s)$ will attain its minimum value there. Otherwise, the minimum value will be attained at $\{(x, y) \in \mathbb{R}^2 \times \mathbb{R}^2 : x = o_k\}$ or $\{(x, y) \in \mathbb{R}^2 \times \mathbb{R}^2 : y = d_k\}$ for some $k \in \{1, 2\}$. For a vector $x = (x_1, x_2)^T$, we define angle $\alpha = \angle(x) \in [0, 2\pi)$ such that $\cos\alpha = x_1/\|x\|_2$ and $\sin\alpha = x_2/\|x\|_2$. We set

$$\alpha_k = \angle(o_k - m),\ \beta_k = \angle(s - d_k)\ for\ k = 1, 2,\ and\ \gamma = \angle(s - m). \tag{3.34}$$

We state the following lemma:

Lemma 1. *For minimum distance* $L(m, s)$ *as defined in (3.18) and attained in* $\mathcal{D}$*, angles as defined in (3.34), and with discount factor* $0 \leq \rho < 1$*, it holds true that*

$$\alpha_1 = \pi - \delta_1\phi + \gamma, \quad \alpha_2 = \pi + \delta_1\phi + \gamma, \tag{3.35}$$

and

$$\beta_1 = \pi - \delta_2\phi + \gamma, \quad \beta_2 = \pi + \delta_2\phi + \gamma, \tag{3.36}$$

where $\phi \in [0, \pi/2]$ *satisfies* $\cos\phi = \rho$*, and* $\delta_k \in \{-1, 1\}$ *for* $k = 1, 2$*.*

Proof. We optimize L with respect to m and s coordinates in the plane; a critical point of $L(m, s)$ satisfies

$$\frac{\partial L}{\partial m_j} = \sum_k \frac{m_j - o_{kj}}{\|m - o_k\|_2} + 2\rho\frac{m_j - s_j}{\|m - s\|_2} = 0 \quad \text{for} \quad j = 1, 2,$$

$$\frac{\partial L}{\partial s_j} = \sum_k \frac{s_j - d_{kj}}{\|s - d_k\|_2} + 2\rho\frac{s_j - m_j}{\|s - m\|_2} = 0 \quad \text{for} \quad j = 1, 2.$$

With reference to the angles α_k, β_k for $k = 1, 2$ and γ as defined in (3.34), we may write

$$\sum_k \cos\alpha_k = \sum_k \cos\beta_k = -2\rho\cos\gamma, \tag{3.37}$$

$$\sum_k \sin\alpha_k = \sum_k \sin\beta_k = -2\rho\sin\gamma. \tag{3.38}$$

Since (3.37) and (3.38) provide

$$\left(\sum_k \cos\alpha_k\right)^2 + \left(\sum_k \sin\alpha_k\right)^2 = 2 + 2\cos(\alpha_2 - \alpha_1) = 4\rho^2,$$

we arrive at $\cos(\alpha_2 - \alpha_1) = 2\rho^2 - 1$. If we set $\phi = \arccos\rho$, then $0 < \phi \le \pi/2$ and $\cos(\alpha_2 - \alpha_1) = \cos 2\phi$. Similarly, we get $\cos(\beta_2 - \beta_1) = \cos 2\phi$. This implies

$$\alpha_2 = \alpha_1 + 2\delta_1\phi, \quad \delta_1 \in \{-1, +1\}, \tag{3.39}$$

$$\beta_2 = \beta_1 + 2\delta_2\phi, \quad \delta_2 \in \{-1, +1\}. \tag{3.40}$$

If we insert (3.39) into (3.37), we obtain $\cos(\alpha_1 + \delta_1\phi) + \cos\gamma = 0$, and if we insert (3.39) into (3.38), we obtain $\sin(\alpha_1 + \delta_1\phi) + \sin\gamma = 0$. We obtain similar results when we insert (3.40) into (3.37) and (3.38). This implies

$$\alpha_1 = \pi - \delta_1\phi + \gamma, \quad \alpha_2 = \pi + \delta_1\phi + \gamma, \tag{3.41}$$

$$\beta_1 = \pi - \delta_2\phi + \gamma, \quad \beta_2 = \pi + \delta_2\phi + \gamma, \tag{3.42}$$

which solves (3.37) and (3.38). Equations (3.39) - (3.42) should be read modulo 2π. □

This in particular implies that $|\alpha_1 - \alpha_2| = |\beta_1 - \beta_2| = 2\phi$, which corresponds to an observation about Steiner trees, where $\rho = 1/2$ and $2\phi = 2\pi/3$; see Winter & Zachariasen (1998).

We now state and prove the following Proposition and hence that $L(m,s)$ attains a unique minimum solution at the critical point for $0 < \rho < 1$, in case such critical point exists in $\mathcal{D}$. For $\rho = 0$, the minimum solution is not unique and minimum distance equals $L(m,s) = \|o_1 - o_2\|_2 + \|d_1 - d_2\|_2$.

Proposition 2. *Whenever $0 < \rho < 1$, the function $(m,s) \mapsto L(m,s)$ is strictly convex, with exception of pairs from the set*

$$\begin{aligned}\mathcal{C} = \{\{(m_1,s_1),(m_2,s_2)\} \in \mathbb{R}^{2+2} \times \mathbb{R}^{2+2} : \angle(o_k - m_1, o_k - m_2) = 0,\\ \angle(m_1 - s_1, m_2 - s_2) = 0,\ \angle(s_1 - d_k, s_2 - d_k) = 0,\ k \in \{1,2\}\}.\end{aligned} \tag{3.43}$$

The critical point of L in $\mathcal{D}$ is not part of any pair in $\mathcal{C}$.

Proof. To show that $L(m,s)$ is strictly convex, we take $(m_1,s_1) \neq (m_2,s_2)$, and write for $0 < \lambda < 1$,

$$L(\lambda m_1 + (1-\lambda)m_2, \lambda s_1 + (1-\lambda)s_2) =$$

$$\sum_k \|o_k - \lambda m_1 - (1-\lambda)m_2\|_2 + 2\rho\|\lambda(m_1 - s_1) + (1-\lambda)(m_2 - s_2)\|_2 +$$

$$\sum_k \|\lambda s_1 + (1-\lambda)s_2 - d_k\|_2 \le$$

$$\lambda \left\{ \sum_k \|o_k - m_1\|_2 + 2\rho\|m_1 - s_1\|_2 + \sum_k \|s_1 - d_k\|_2 \right\} +$$

$$(1-\lambda) \left\{ \sum_k \|o_k - m_2\|_2 + 2\rho\|m_2 - s_2\|_2 + \sum_k \|s_2 - d_k\|_2 \right\} =$$

$$\lambda L(m_1, s_1) + (1-\lambda)L(m_2, s_2).$$

The inequality is strict when the pairs $((m_1, s_1), (m_2, s_2))$ satisfy either $\angle(o_k - m_1, o_k - m_2) \neq 0$, or $\angle(m_1 - s_1, m_2 - s_2) \neq 0$, or $\angle(s_1 - d_k, s_2 - d_k) \neq 0$ for some $k \in \{1, 2\}$, i.e., the pairs are outside the set $\mathcal{C}$.

The set $\mathcal{C}$ consists of those pairs $((m_1, s_1), (m_2, s_2))$ for which o_1, o_2, m_1, m_2 are on a single line M, s_1, s_2, d_1, d_2 are on another single line S, and m_1, s_1 and m_2, s_2 are on parallel lines. We prove that such points are never critical points in $\mathcal{D}$. In case either $(m_1, s_1) \in \mathcal{D}$ or $(m_2, s_2) \in \mathcal{D}$ is a critical point, then this results in a contradiction by Lemma 1, since for instance $\angle(o_1 - m_j, o_2 - m_j) = 2\phi$ for $j \in \{1, 2\}$, with $0 < 2\phi < \pi$. This implies that the pairs in set $\mathcal{C}$ never contain a critical point in $\mathcal{D}$. □

Proof of Theorem 3 We use the result of Lemma 1 in our representation of the platooning paths in the complex plane; we write

$$L = \lambda_1 + \lambda_2 + 2\rho\sigma + \mu_1 + \mu_2,$$

where $\lambda_k = \|o_k - m\|_2$, $\mu_k = \|s - d_k\|_2$ for $k = 1, 2$, and $\sigma = \|m - s\|_2$. We write unit numbers $u_\delta = e^{i(\pi+\delta\phi+\gamma)} = -e^{i(\delta\phi+\gamma)}$ with $\delta \in \{-1, +1\}$, and $v = e^{i\gamma}$; see also Figure 3.13.

This implies

$$o_1 = m + \lambda_1 u_{-\delta_1} = m - \lambda_1 e^{i(-\delta_1\phi+\gamma)},$$

$$o_2 = m + \lambda_2 u_{+\delta_1} = m - \lambda_2 e^{i(+\delta_1\phi+\gamma)}.$$

We also write $s = m + \sigma e^{i\gamma}$, and

$$d_1 = s - \mu_1 u_{-\delta_2} = m + \sigma e^{i\gamma} + \mu_1 e^{i(-\delta_2\phi+\gamma)},$$

$$d_2 = s - \mu_2 u_{+\delta_2} = m + \sigma e^{i\gamma} + \mu_2 e^{i(+\delta_2\phi+\gamma)}.$$

The differences $\Delta_o = o_2 - o_1 = r_o e^{i\varphi_o}$, $\Delta_d = d_2 - d_1 = r_d e^{i\varphi_d}$, and $\Delta_1 = d_1 - o_1 = r_1 e^{i\varphi_1}$ are given by the inital data, and $\Delta_2 = d_2 - o_2 = \Delta_d - \Delta_o + \Delta_1$. Note

$$\Delta_o = o_2 - o_1 = (\lambda_1 e^{-i\delta_1\phi} - \lambda_2 e^{i\delta_1\phi})e^{i\gamma} = r_o e^{i\varphi_o},$$

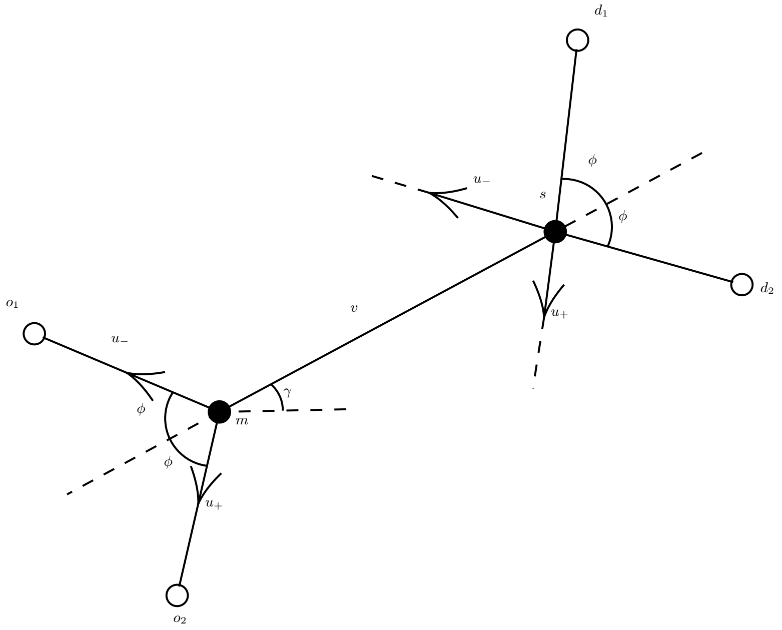


Figure 3.13: Platooning distance optimization in $\mathbb{C}$

which implies

$$r_o e^{i(\varphi_o-\gamma)} = \lambda_1 e^{-i\delta_1\phi} - \lambda_2 e^{i\delta_1\phi}.$$

By taking real and imaginary parts of this equality, we get

$$\lambda_1 + \lambda_2 = -r_o \frac{\sin(\varphi_o-\gamma)}{\sin\delta_1\phi}, \tag{3.44}$$

$$\lambda_1 - \lambda_2 = r_o \frac{\cos(\varphi_o-\gamma)}{\cos\delta_1\phi}. \tag{3.45}$$

Solving this set of linear equations in λ_1 and λ_2, we arrive at

$$\lambda_1 = -r_o \frac{\sin(\varphi_o-\gamma-\delta_1\phi)}{\sin 2\delta_1\phi}, \tag{3.46}$$

$$\lambda_2 = -r_o \frac{\sin(\varphi_o-\gamma+\delta_1\phi)}{\sin 2\delta_1\phi}. \tag{3.47}$$

As we assumed $\lambda_k \geq 0$ for $k \in \{1,2\}$, we need to ascertain that $\lambda_1+\lambda_2 \geq 0$. This holds true by (3.44) if and only if $\delta_1 = -\operatorname{sgn}\sin(\varphi_o-\gamma)$. In addition, we need to show that $\lambda_1\lambda_2 \geq 0$, which is equivalent to

$$r_o^2 \frac{\sin(\varphi_o-\gamma-\delta_1\phi)\sin(\varphi_o-\gamma+\delta_1\phi)}{\sin^2\delta_1\phi} \geq 0,$$

or, using trigonometric identities,

$$\sin^2(\varphi_o - \gamma)\cos^2\phi - \cos^2(\varphi_0 - \gamma)\sin^2\phi \geq 0,$$

which means that

$$\tan^2(\varphi_o - \gamma) \geq \tan^2\phi = \frac{1-\rho^2}{\rho^2}. \tag{3.48}$$

A similar analysis of Δ_d provides

$$\mu_1 = r_d \frac{\sin(\varphi_d - \gamma - \delta_2\phi)}{\sin 2\delta_2\phi}, \tag{3.49}$$

$$\mu_2 = r_d \frac{\sin(\varphi_d - \gamma + \delta_2\phi)}{\sin 2\delta_2\phi}. \tag{3.50}$$

For $\mu_1 + \mu_2 \geq 0$ it is necessary and sufficient that $\delta_2 = \operatorname{sgn}\sin(\varphi_d - \gamma)$, and $\mu_1\mu_2 \geq 0$ is equivalent to

$$\tan^2(\varphi_d - \gamma) \geq \tan^2\phi = \frac{1-\rho^2}{\rho^2}. \tag{3.51}$$

We have now expressed λ_k and μ_k for $k = 1, 2$ in terms of the initial data and γ. To express σ also in the same terms, and to solve for γ, we analyse Δ_1 as follows.

$$\Delta_1 = d_1 - o_1 = \sigma e^{i\gamma} + \mu_1 e^{i(\gamma - \delta_2\phi)} + \lambda_1 e^{i(\gamma - \delta_1\phi)} = r_1 e^{i\varphi_1}.$$

This implies

$$r_1 e^{i(\varphi_1 - \gamma)} = \sigma + \mu_1 e^{-i\delta_2\phi} + \lambda_1 e^{-i\delta_1\phi}.$$

If we take the real part and rearrange terms, we get

$$\sigma = r_1\cos(\varphi_1 - \gamma) - (\lambda_1 + \mu_1)\cos\phi. \tag{3.52}$$

If we take the imaginary part, we arrive at

$$r_1\sin(\varphi_1 - \gamma) = -\mu_1\sin\delta_2\phi - \lambda_1\sin\delta_1\phi.$$

If we insert (3.46) and (3.49) in this equation, and use trigonometric identities, we get $A\cos\gamma = B\sin\gamma$ with

$$A = 2r_1\sin\varphi_1\cos\phi + r_d\sin(\varphi_d - \delta_2\phi) - r_o\sin(\varphi_o - \delta_1\phi), \tag{3.53}$$

$$B = 2r_1\cos\varphi_1\cos\phi + r_d\cos(\varphi_d - \delta_2\phi) - r_o\cos(\varphi_o - \delta_1\phi), \tag{3.54}$$

and hence

$$\gamma = \arctan\frac{A}{B} + \delta_3\pi, \tag{3.55}$$

where $\delta_3 \in \{-1, 1\}$. This proves the theorem. □

Observe that when γ is replaced by $\gamma + \pi$, equations (3.46) - (3.52) change signs. This will be used, together with choice of δ_1 and δ_2 to ensure that λ_k and μ_k are non-negative for $k = 1, 2$, while sign of σ may be negative in case platooning distance is larger than direct trucking distances.

We now finally consider the cases when $o_k = m$ or $s = d_k$ for some $k \in \{1, 2\}$, say $k = 1$. We discuss the case of $o_1 = m$ in detail. The other cases follow similar lines. If $o_1 = m$, then

$$L(m, s) = L(s) = \|o_1 - o_2\|_2 + 2\rho\|o_1 - s\|_2 + \sum_k \|s - d_k\|_2,$$

and we get

$$\frac{\partial L}{\partial s_j} = 2\rho \frac{s_j - o_{1j}}{\|s - o_1\|_2} + \sum_k \frac{s_j - d_{kj}}{\|s - d_k\|_2} = 0, \quad j = 1, 2.$$

This implies, with $\beta_k = \angle(s - d_k)$ and $\gamma = \angle(o_1 - s)$, that $\beta_1 = \pi + \delta\phi + \gamma$ and $\beta_2 = \pi - \delta\phi + \gamma$ for some $\delta \in \{1, 2\}$. We may write $L = r_0 + 2\rho\sigma + \mu_1 + \mu_2$ with μ_1 as in (3.49) and μ_2 as in (3.50). Note that

$$\Delta_1 = d_1 - o_1 = \sigma e^{i\gamma} - \mu_1 e^{i\beta_1} = \sigma e^{i\gamma} + \mu_1 e^{-i\delta + \gamma} = r_1 e^{i\varphi_1},$$

so

$$r_1 e^{i\varphi_1 + \gamma} = \sigma + \mu_1 e^{-i\phi}.$$

Taking the real part provides $r_1 \cos(\varphi_1 - \gamma) = \sigma + \mu_1 \cos\phi$, and hence

$$\sigma = r_1 \cos(\varphi_1 - \gamma) - \mu_1 \cos\phi.$$

Taking the imaginary part results in $r_1 \sin(\varphi_1 - \gamma) = -\mu_1 \sin\delta\phi$, we get, after substitution of the RHS of (3.49) and trigonometric manipulations,

$$\{2r_1 \sin\varphi_1 \cos\phi + r_d \sin(\varphi_d - \delta\phi)\} \cos\gamma = \{2r_1 \cos\varphi_1 \cos\phi + r_d \cos(\varphi_d - \delta\phi)\} \sin\gamma.$$

With

$$A = 2r_1 \sin\varphi_1 \cos\phi + r_d \sin(\varphi_d - \delta\phi),$$

$$B = 2r_1 \cos\varphi_1 \cos\phi + r_d \cos(\varphi_d - \delta\phi),$$

we arrive at

$$\gamma = \arctan\frac{A}{B} + \delta'\pi,$$

with $\delta' \in \{-1, 1\}$.

Proof of Theorem 4. Given that $o_1 = m + \lambda_1 u_{-\delta_1}$, $o_2 = m + \lambda_2 u_{+\delta_1}$, $d_1 = m + \sigma v - \mu_1 u_{-\delta_2}$, and $d_2 = m + \sigma v - \mu_2 u_{+\delta_2}$, with $v = -\frac{1}{2\rho}(u_{-1} + u_{+1})$, we may write any convex combination (we write $\theta = \frac{\sigma}{2\rho}$) as

$$x = a_1 o_1 + a_2 o_2 + b_1 d_1 + b_2 d_2 =$$

$$m + a_1\lambda_1 u_{-1} + a_2\lambda_2 u_{+1} - (b_1+b_2)\theta(u_{-1}+u_{+1}) - b_1\mu_1 u_{+1} - b_2\mu_2 u_{-1} =$$

$$m + \{a_1\lambda_1 - (b_1+b_2)\theta - b_2\mu_2\}u_{-1} + \{a_2\lambda_2 - (b_1+b_2)\theta - b_1\mu_1\}u_{+1}.$$

We have assumed here that $\delta_1 = +1$ and $\delta_2 = -1$. First, we find a convex combination for which $x = m$, which is a solution to

$$\begin{pmatrix} \lambda_1 & 0 & -\theta & -\theta-\mu_2 \\ 0 & \lambda_2 & -\theta-\mu_1 & -\theta \\ 1 & 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}.$$

Gaussian elimination gives

$$\begin{pmatrix} 1 & 0 & 0 & -z_{22}/w_{11} \\ 0 & 1 & 0 & z_{11}/w_{11} \\ 0 & 0 & 1 & w_{22}/w_{11} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} \lambda_2\theta/w_{11} \\ \lambda_1(\mu_1+\theta)/w_{11} \\ \lambda_1\lambda_2/w_{11} \end{pmatrix},$$

with $(i, j \in \{1,2\})$

$$w_{ij} = \lambda_i\mu_j + \lambda_1\lambda_2 + \lambda_1\theta + \lambda_2\theta,$$

$$z_{ij} = \lambda_i\mu_j + \mu_1\mu_2 + \mu_1\theta + \mu_2\theta.$$

If we put $b_2 = 0$, we find that $a_1 = \lambda_2\theta/w_{11}$, $a_2 = \lambda_1(\mu_1+\theta)/w_{11}$, and $b_1 = \lambda_1\lambda_2/w_{11}$ are indeed coefficients of a convex combination, i.e., $a_1, a_2, b_1 \in [0,1]$ and $a_1 + a_2 + b_1 = 1$.

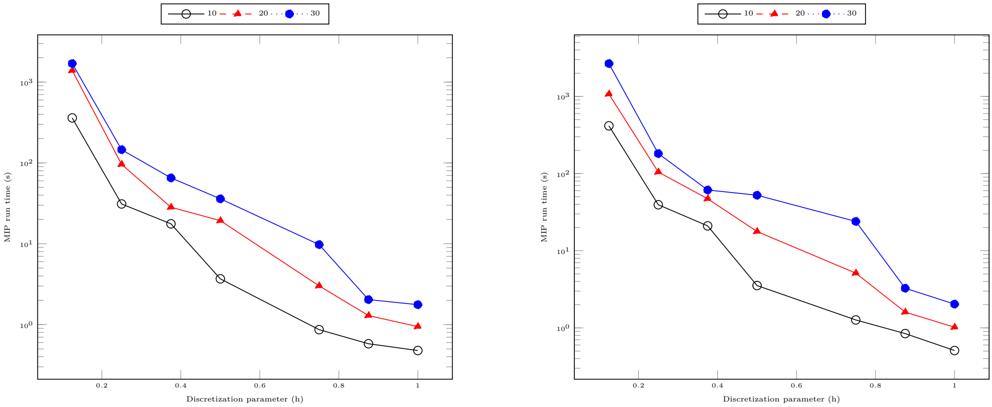
Second, we find a convex combination for which $x = s = m + \sigma v$, which is a solution to

$$\begin{pmatrix} \lambda_1 & 0 & -\theta & -\theta-\mu_2 \\ 0 & \lambda_2 & -\theta-\mu_1 & -\theta \\ 1 & 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} -\theta \\ -\theta \\ 1 \end{pmatrix}.$$

Gaussian elimination now gives

$$\begin{pmatrix} 1 & 0 & 0 & -z_{22}/w_{11} \\ 0 & 1 & 0 & z_{11}/w_{11} \\ 0 & 0 & 1 & w_{22}/w_{11} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} -\mu_1\theta/w_{11} \\ \mu_1(\lambda_1+\theta)/w_{11} \\ (\lambda_1\lambda_2 + \lambda_1\theta + \lambda_2\theta)/w_{11} \end{pmatrix}.$$

If we put $b_2 = \mu_1\theta/z_{22}$, we find that $a_1 = 0$, $a_2 = \mu_1\mu_2/z_{22}$, and $b_1 = \mu_2(\lambda_2+\theta)/z_{22}$ are indeed coefficients of a convex combination, i.e., $a_2, b_1, b_2 \in [0,1]$ and $a_2 + b_1 + b_2 = 1$. We



(a) $(2, \infty)$ **(b)** $(3, \infty)$

Figure 3.14: Run times for differing discretization parameters

would have arrived at the same outcomes in the case when $\delta_1 = +1$ and $\delta_2 = -1$, as the roles of u_+ and u_- would have been switched.

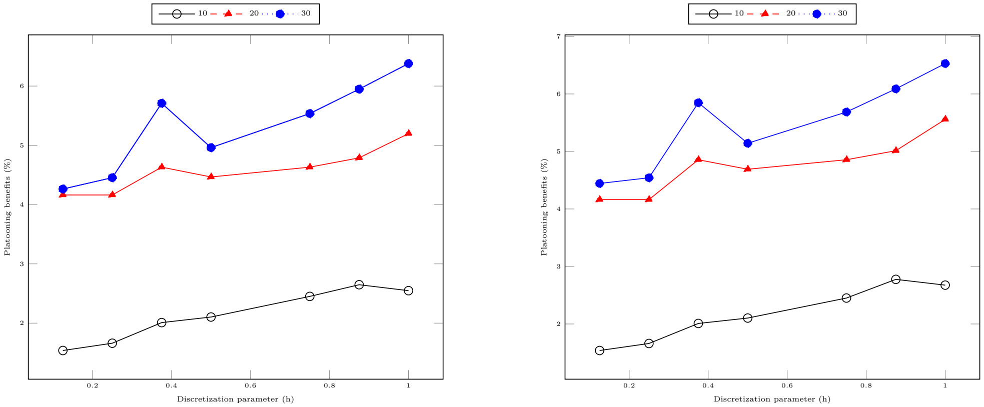
We now do the analysis for $\delta_1 = \delta_2 = 1$ (and the analysis of $\delta_1 = \delta_2 = -1$ will yield the same results). Similar to above, if we put $x = m$ we can do the Gaussian elimination and arrive at $b_2 = 0$, $a_1 = \lambda_2(\theta + \mu_1)/w_{21}$, $a_2 = \lambda_1\theta/w_{21}$, and $b_1 = \lambda_1\lambda_2/w_{21}$, which again yields a convex combination.

If we put $x = m + \sigma v$, a convex combination is provided by $a_1 = 0$, $a_2 = \mu_1\mu_2/z_{21}$, $b_1 = \mu_2\theta/z_{21}$, and $b_2 = \mu_1(\lambda_2 + \theta)/z_{21}$. This proves the theorem. □

3.10.2 Impact of the discretization parameter

A finer discretization would provide a higher quality solution that is closer to the continuous time case but lead to an increase in the problem size, potentially to the point of intractability. On the flip side, a less fine discretization level would keep the problem size in check while compromising on the solution quality. Here, we check the effect of the discretization parameter on the system savings. To do so, we run the MIP from phase 1 for different discretization parameters between 7.5 minutes and 60 minutes. We report percentage savings for the $(3, \infty)$ and $(2, \infty)$ settings in Figure 3.15 and run times in Figure 3.14. Note that we have used a logarithmic y-axis in Figure 3.14.

From the run times in Figure 3.14, the increase in problem size with a finer level of discretization for both for both settings is evident. This increase is especially pronounced and becomes larger as we continue lowering the values of the discretization parameter. For example, the $(3, \infty)$ run time increases by a factor of fifteen from about 180 seconds to about



(a) $(2, \infty)$ **(b)** $(3, \infty)$

Figure 3.15: Percentage benefits for differing discretization parameters; 30 trucks; $\rho = 0.9$

2700 seconds. This huge increase does not have much of an effect on the percentage benefits as we can see in Figure 3.15. This holds true for $(2, \infty)$ as well. Based on this, we use a discretization parameter of 0.25 in our experiments.

4 Scenario-based Platoon Lane Network Design

4.1 Introduction

The cost-effective design of appropriate levels of road, public transit, and service network infrastructure is a key aspect of urban planning. Infrastructure design typically involves long-term decisions and uncertainty about the (future) demand that the infrastructure has to support. Furthermore, in most settings, infrastructure modifications at a later date are expensive (or even impossible). Consequently, it is critical that methods to support infrastructure design decisions take uncertainty into account (Hewitt et al., 2021).

Thus, stochastic models are most appropriate as they explicitly capture the uncertainty; deterministic equivalents that optimize using a point estimate of demand may perform poorly for realizations that differ substantially from the point estimate (Wang et al., 2019b). When the probability distribution capturing the uncertainty is known, one way of representing (some of) the uncertainty in optimization models is by means of sampled scenarios (Hewitt et al., 2021; Birge & Louveaux, 2011).

In scenario-based planning, there is a trade-off between solve time and solution quality. Using more scenarios captures more of the uncertainty and is likely to produce higher-quality solutions, i.e., more robust solutions, but also increases instance sizes and is likely to result in longer solve times. For complex problems, it can become computationally prohibitive to find solutions using more than only a few scenarios. The literature has proposed different approaches to deal with this trade-off. For example, Karuppiah et al. (2010) select a subset of the scenarios based on their probabilities of occurrence, Hewitt et al. (2021) reduce the number of scenarios by clustering the ones that lead to similar decisions, and Bakir et al. (2020) partition the scenario set into subsets based on partition dual bounds. The well-known sample average approximation method (Kleywegt et al., 2002) repeatedly solves instances with small sets of randomly chosen scenarios. In approaches that repeatedly solve instances with small sets of randomly chosen scenarios it is common to return the best solution from among the solutions obtained for the different instances. In this paper, we go beyond that and explore the benefit of blending the solutions encountered, i.e., extracting and combining the most valuable components of the solutions obtained for the different instances. A similar idea was discussed by Dembo (1991) but to the best of our knowledge has not been further examined. In this paper, we explore this concept in the context of a network design problem for truck platoon infrastructure and demonstrate its efficacy in a computational study.

A truck platoon is a set of trucks that drive at short headways behind one another. The following trucks drive automatically behind the leading truck using advanced cruise control technology. Trucks in a platoon consume less fuel, which in turn reduces costs and emissions. Furthermore, since they drive at short headways, they occupy less space thereby improving traffic throughput (Schladover et al., 2015; Van Arem et al., 2006). In future phases of deployment, it may no longer be needed to have (attentive) drivers in the following trucks, which creates labor costs savings (Bhoopalam et al., 2018; Kilcarr, 2016).

Despite the potential benefits of platooning, road operators have raised concerns about the impact of platoons on surrounding traffic (Wang et al., 2019a). Real-life tests (Andersson et al., 2017) and simulation studies (Guoy et al., 2014) indicate that vehicles around truck platoons mimic their behavior by maintaining a short headway or by cutting in between the trucks in a platoon, which can be dangerous. One way to reduce the interaction with other vehicles, and thus allow longer and more effective platoons, is to separate truck platoons from surrounding traffic by operating dedicated platoon lanes (Wang et al., 2019a; Tsugawa et al., 2016). The use of dedicated lanes has also been proposed to support the deployment of automated vehicles (Rad et al., 2020). Such dedicated lanes could incorporate sophisticated traffic control systems, such as C-ITS, to help facilitate less human involvement in the lateral control of platoons (Krechmer, 2016). Moreover, dedicated platoon lanes may reduce the wear and tear of the (part of the) roads for regular traffic (Mallick & El-Korchi, 2013). In this paper, we focus on the problem of deciding which segments of a road network to upgrade and provide dedicated platooning lanes.

While the transportation network design problem has received considerable attention (Magnanti & Wong, 1984), we are not aware of any paper that specifically considers the truck platooning context. Several papers (Chen et al., 2016b, 2017; Madadi et al., 2020) focus on locating automated vehicle links or zones in road networks for passenger autonomous vehicle from a traffic flow perspective. Scherr et al. (2019, 2020) consider such AV zones in the service network design problem with mixed autonomous fleets where they have two types of vehicles - manually operated (MV) and autonomous (AV). The AVs can operate independently in the AV zones and drive in an MV led platoon everywhere else. They assume the AV zones are known and point out the location of such zones as a relevant future research direction.

In this paper, we use the platoon lane network design setting to explore our novel scenario-based planning approach. More specifically, our contributions are that (i) we present a computationally efficient approach that blends components of multiple network designs, each generated using a small set of scenarios, to obtain a robust network design, (ii) we introduce the Platoon Lane Network Design Problem (PLNDP), i.e., the problem of designing a network of dedicated lanes to support truck platooning, and provide an integer programming formulation, and (iii) we conduct numerical experiments to study the performance of our solution blending approach across a diverse set of instances.

The remainder of this paper is structured as follows. Section 4.2 describes the Platoon Lane Network Design Problem. We then present our solution blending approach in Section 4.3. Next, we evaluate the performance of our solution blending approach and analyze the benefits of dedicated platoon lanes in different settings in an extensive computational study in Section 4.4. Finally, we discuss future research directions in Section 4.5.

4.2 Problem description

We model the PLNDP on a graph $\mathcal{G} = (\mathcal{V}, \mathcal{A})$ with non-negative arc lengths. The set of vertices $\mathcal{V}$ represents the locations, i.e., the possible origins and destinations of trucks. The set of arcs $\mathcal{A}$ represents the road segments that connect the different locations. There are two types of arcs: *regular arcs* and *platoon lane arcs*. A trucks can drive by itself on any arc in the network but can drive in a platoon only on a platoon lane arc.

Consider a set of trucks $\mathcal{K}$. The cost for a truck traveling by itself on an arc a is c_a, which we assume is proportional to the length of arc a. The cost for a truck traveling in a platoon on a platoon lane arc a is $c_a^p = \rho c_a$ where $\rho \in (0.5, 1)$ is the fuel consumption factor. The fuel consumption factor ρ cannot be less than 0.5 since the total combined fuel consumption of a 2-truck (or higher) platoon cannot be lower than that of a truck driving alone. We use this simple cost structure for ease of exposition and do not differentiate between leaders and followers. Cost structures that differentiate the fuel savings for leaders and followers can be accommodated.

The PLNDP involves determining which of the arcs in the network should be platoon arcs. Upgrading a regular arc to a platoon arc incurs a cost and we assume a limited budget is available. Therefore, determining which arcs to upgrade is nontrivial. We refer to a set of platoon lane arcs as a *network design*. Given a network design, we can determine routes for each of the trucks that minimize the total fuel consumption costs. We refer to this step as the *Platoon Routing Problem* (PRP). Next, we elaborate on these these two problems.

4.2.1 Platoon Lane Network Design Problem (PLNDP)

The PLNDP involves determining the set of platooning lane arcs, i.e, on which arcs in $\mathcal{A}$ to operate a platooning lane. Adding a platooning lane to arc $a \in \mathcal{A}$ costs f_a. The available budget for adding platooning lanes is B. The cost f_a for "adding a platooning lane" can capture various different settings. It can capture physically adding a lane, i.e., building a separate dedicated platooning lane, but it can also capture taking an existing lane and reserving it for use by platoons, in which case the cost may also include a component that represents the negative impact on regular traffic. There may also be settings in which a lane can be used by both platoons and regular traffic, but where additional technology is installed that can help ensure safety.

As mentioned earlier, infrastructure design decisions such as these are subject to uncertainty. Here, this uncertainty is in terms of the trucks needing to use the infrastructure, e.g., the number of trucks as well as their origin, destination, earliest possible departure time at the origin, and the latest allowed arrival time at the destination. We model this uncertainty by means of a set of scenarios each with a probability of occurrence. Let the set of scenarios be denote by $\mathcal{S}$ and the probability of occurrence of scenario $s \in \mathcal{S}$ be denoted by p_s. In a scenario $s \in \mathcal{S}$, a truck $k \in \mathcal{K}_s$ has origin $o_k^s \in \mathcal{V}$ and destination $d_k^s \in \mathcal{V}$. Temporal information for truck $k \in \mathcal{K}_s$ includes its earliest possible departure time a_k^s from its origin o_k^s and its latest allowed arrival time l_k^s at its destination d_k^s. We assume that trucks and platoons traverse arcs at a constant speed (identical for trucks and platoons). Thus trucks can only wait at nodes and platoons are only formed (and dissolved) at nodes.

The PLNDP is a two-stage stochastic program (see Ahmed (2010)), where the selection of arcs to upgrade to platooning arcs is captured in the first stage and where the routing of the trucks (for each scenario) is captured in the second stage. We next formulate this two-stage stochastic program as an integer program.

To be able to capture time, we switch to using a time-expanded network rather than a flat network. That is, we create graph $\mathcal{G}_\mathcal{T} = (\mathcal{V}_\mathcal{T}, \mathcal{A}_\mathcal{T} \cup \mathcal{H}_\mathcal{T})$ in which time is discretized into periods of equal length $\triangle$ and with time points $\mathcal{T} = 0, \triangle, 2\triangle, 3\triangle, \ldots, H\triangle$. The number of time periods, H, is determined by first finding the smallest e_k^s among the trucks in $\mathcal{K}_s$ and shifting the earliest possible departure time and latest allowed arrival time of each truck backward by that amount. The largest l_k^s among the trucks in $\mathcal{K}_s$ then implies H as follows: $H = \lceil \frac{\max_{k \in \mathcal{K}, s \in \mathcal{S}} l_k^s}{\triangle} \rceil$. The time-expanded network $\mathcal{G}_\mathcal{T}$ has a copy u_i of each node $u \in \mathcal{V}$ for each of the time points $i \in \mathcal{T}$ and so $|\mathcal{V}_\mathcal{T}| = (H+1) \cdot |\mathcal{V}|$. The time-expanded network $\mathcal{G}_\mathcal{T}$ has two types of arcs: $\mathcal{A}_\mathcal{T}$ and $\mathcal{H}_\mathcal{T}$. An arc $a \in \mathcal{A}_\mathcal{T}$ connects two nodes $u_i, v_j \in \mathcal{V}_\mathcal{T}$ such that $j = i + \lceil t_{uv}/\triangle \rceil$. These arcs represent the movement of a truck in both space and time. An arc $a \in \mathcal{H}_\mathcal{T}$ connects two nodes $u_{i\triangle}, u_{(i+1)\triangle} \in \mathcal{V}_\mathcal{T}$. These arcs represent the movement of a truck in time only, i.e., the truck waits.

Let design variable y_a be 1 if arc a is chosen to add a platooning lane to, and 0 otherwise and let design variable y_a^{ts} be 1 if arc a is traversed by a platoon at time t in scenario s, and 0 otherwise. Furthermore, let routing variable w_{ak}^{ts} be 1 if truck k traverses arc a by itself at time t in scenario s and routing variable x_{ak}^{ts} be 1 if truck k traverse arc a in a platoon at time t in scenario s.

The formulation of PLNDP can be found below, where $\delta^+(v)$ denotes the set of arcs with tail at node v and $\delta^-(v)$ denotes the set of arcs with head at node v:

$$\min \quad \sum_{s\in\mathcal{S}} p_s \left(\sum_{a\in\mathcal{A}} \sum_{t\in\mathcal{T}} \sum_{k\in\mathcal{K}_s} \left(c_a w_{ak}^{ts} + c_a^p x_{ak}^{ts} \right) \right) \tag{4.1}$$

$$\sum_{a\in\delta^+(v)} (w_{ak}^{ts} + x_{ak}^{ts}) - \sum_{a\in\delta^-(v)} (w_{ak}^{(t-t_a)s} + x_{ak}^{(t-t_a)s}) = \begin{cases} 1 & (v,t) = (o_k^s, a_k^s) \\ -1 & (v,t) = (d_k^s, l_k^s) \\ 0 & otherwise \end{cases} \quad \forall v\in\mathcal{V}, t\in\mathcal{T}, k\in\mathcal{K}_s, s\in\mathcal{S} \tag{4.2}$$

$$\sum_{k\in\mathcal{K}} x_{ak}^{ts} \geq 2 - |\mathcal{K}_s|(1 - y_a^{ts}) \quad \forall a\in\mathcal{A}, t\in\mathcal{T}, s\in\mathcal{S} \tag{4.3}$$

$$x_{ak}^{ts} \leq y_a \quad \forall a\in\mathcal{A}, k\in\mathcal{K}_s, t\in\mathcal{T}, s\in\mathcal{S} \tag{4.4}$$

$$y_a^{ts} \leq y_a \quad \forall a\in\mathcal{A}, t\in\mathcal{T}, s\in\mathcal{S} \tag{4.5}$$

$$\sum_{a\in\mathcal{A}} f_a y_a \leq B \tag{4.6}$$

$$w_{ak}^{ts}, x_{ak}^{ts} \in \{0,1\} \quad \forall a\in\mathcal{A}, k\in\mathcal{K}_s, t\in\mathcal{T}, s\in\mathcal{S} \tag{4.7}$$

$$y_a^{ts} \in \{0,1\} \quad \forall a\in\mathcal{A}, t\in\mathcal{T}, s\in\mathcal{S} \tag{4.8}$$

$$y_a \in \{0,1\} \quad \forall a\in\mathcal{A} \tag{4.9}$$

The objective function (4.1) seeks to minimize total expected travel costs. Constraints (4.2) are flow conservation constraints that ensure that trucks leave their origins and arrive at their destinations as per schedule. Constraints (4.3) and (4.4) ensure that if there is a platoon on an arc, there are at least two trucks involved and that said arc has a platooning lane. Here, constraints (4.3) can be implemented as lazy constraints. That is, they will not be active until a feasible solution is found. The feasible solution found is then checked against them and in case these constraints are violated, the solution is discarded and the constraints are added to the formulation and the formulation is resolved. Constraints (4.5) make sure that any arc traversed by a platoon has a platooning lane. Constraints (4.6) make sure that budget restrictions are respected. The domains of decision variables are specified by constraints (4.7), 4.8, and (4.9).

4.2.2 Platoon Routing Problem (PRP)

Given a platoon lane network design, we can determine the *route plan* for the different trucks for a certain scenario by solving an instance of the PRP. A route plan specifies the paths from origins to destinations, the time schedules, and which trucks platoon together in different parts of the network. Each truck trip $k \in \mathcal{K}$ has origin o_k, destination d_k, earliest departure time a_k, and latest arrival time l_k.

The formulation of the PRP is again based on a time-expanded network $\mathcal{G}_{\mathcal{T}} = (\mathcal{V}_{\mathcal{T}}, \mathcal{A}_{\mathcal{T}} \cup \mathcal{H}_{\mathcal{T}})$. Here, we have only have the routing related decision variables, i.e., w^t_{ak}, which is 1 if truck k begins traveling on arc a by itself at time t, and x^t_{ak}, which is 1 if truck k begins traveling on arc a at time t in a platoon. From the solution to the PLNDP we have y_a, which is 1 if arc a was set to be a platoon lane arc, and 0 otherwise. The IP formulation is below:

$$\min \quad \sum_{a\in\mathcal{A}} \sum_{t\in\mathcal{T}} \sum_{k\in\mathcal{K}_s} \left(c_a w^t_{ak} + c^p_a x^t_{ak}\right) \tag{4.10}$$

$$\sum_{a\in\delta^+(v)} (w^t_{ak} + x^t_{ak}) - \sum_{a\in\delta^-(v)} (w^{(t-t_a)}_{ak} + x^{(t-t_a)}_{ak}) = \begin{cases} 1 & (v,t) = (o_k, a_k) \\ -1 & (v,t) = (d_k, l_k) \\ 0 & otherwise \end{cases} \quad \forall v \in \mathcal{V}, t \in \mathcal{T}, k \in \mathcal{K}, \tag{4.11}$$

$$\sum_{k\in\mathcal{K}} x^t_{ak} \geq 2 - |\mathcal{K}|(1 - y_a) \qquad \forall a \in \mathcal{A}, t \in \mathcal{T} \tag{4.12}$$

$$\sum_{k\in\mathcal{K}} x^t_{ak} \leq |\mathcal{K}| y_a \qquad \forall a \in \mathcal{A}, t \in \mathcal{T}, \tag{4.13}$$

$$w^t_{ak}, x^t_{ak} \in \{0,1\} \qquad \forall a \in \mathcal{A}, k \in \mathcal{K}, t \in \mathcal{T} \tag{4.14}$$

The objective function (4.10) seeks to minimize the total travel costs. Constraints (4.11) are a set of flow conservation constraints that ensure trucks leave their origins and arrive at their destinations as per schedule. Again, Constraints (4.12) and (4.13) ensure that if there is a platoon on an arc, there are at least two trucks involved and that said arc has a platooning lanes. Constraints (4.14) specify the domains of the decision variables.

4.3 A design blending approach

We can use a commercial solver to solve the IP in Section 4.2.1 to generate network designs. Using more demand scenarios would create a more robust network design, i.e., a network design that is likely to result in higher platooning benefits in practice. However, at the same time, using more scenarios increases the problem size and computational requirements (Wang et al., 2019b; Hewitt et al., 2021). In this section, we outline our design blending framework for creating high-quality designs with relatively low computational requirements.

The framework is motivated, in part, by the following observations:

Observation 1. *Generating M designs using N scenarios tends to be faster than generating a single design using MN scenarios*

Observation 2. *Evaluating a design takes much less time than generating a design.*

The framework has three steps, as shown in Figure 4.1, and is controlled by two parameters M and N. In the first step, PLNDP is solved M times, each time with N randomly drawn scenarios from $\mathcal{S}$. In the second step, the resulting M designs are analyzed and a score is computed for each arc indicating the benefit of including that arc in a design. In the third and last step, these arc scores are used to obtain a final "blended" design (as it consists of components of the initial M designs).

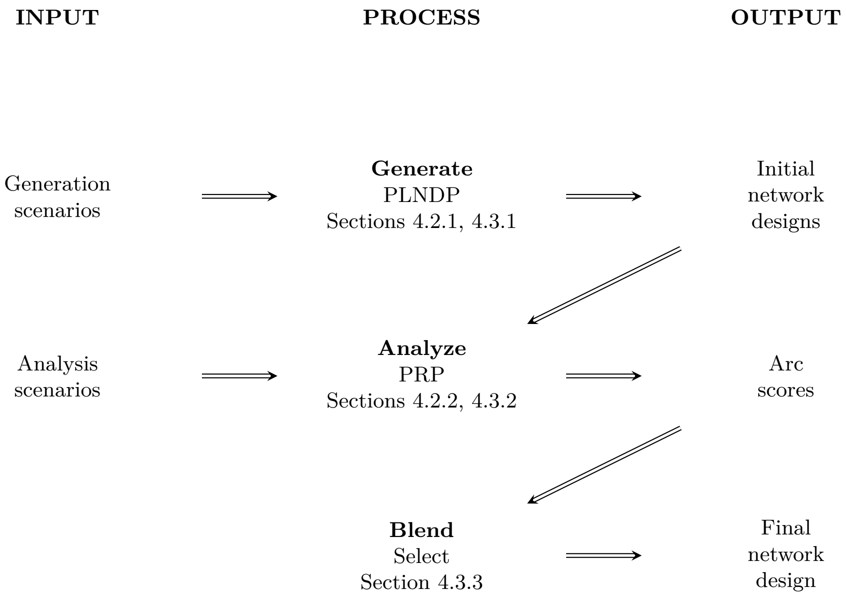


Figure 4.1: Design blending framework

4.3.1 Generate

In this first step, we start by randomly selecting NM scenarios from $\mathcal{S}$, which we refer to as the set of generation scenarios. Next, we solve M instances of PLNDP, each with N of the generation scenarios, to obtain M platoon lane network designs.

As mentioned earlier, using more scenarios (i.e., a higher value of N) increases the instance size and, thus, the time to solve the instance. Therefore, we prefer to use a low value of N. However, using a small value of N is likely to lead to less robust network designs since the representation of the uncertainty may not be very accurate. In the next step, we evaluate the performance of the M designs and analyze the contribution to the performance of each of the arcs chosen to be upgraded to a platoon lane in the design.

4.3.2 Analyze

In this second step, we start by randomly selecting N_e scenarios from $\mathcal{S}$, which we refer to as the set of analysis scenarios $\mathcal{S}_a$. Next, we evaluate the performance of each of the M platoon lane network designs on the (same) set of analysis scenarios. To do so, we solve the PRP from Section 4.2.2 for each of the analysis scenarios. Because the platooning lanes are fixed when evaluating a given network design, only the route plan for the trucks in a given analysis scenario has to be determined, which can be done efficiently. Thus, the number of analysis scenarios N_e can be chosen much larger than the number of generation scenarios N used to create a network design.

Importantly, the purpose of the analysis is not solely to identify the platooning lane network design that performs best, i.e., results in highest average savings across the analysis scenarios, but to analyze the “contribution” of a platooning lane to the performance of a network design. To do this, we compute various statistics for each of the platooning lanes in a design and use these statistics to compute a score for each arc.

For simplicity, we assess the value of individual (platooning) arcs rather than more complex structures (e.g., connected components of platooning arcs). Let $\mathcal{A}_p'$ denote the union of the platoon lane arcs in the M network designs. We consider three ways to compute a score w_a for arc $a \in \mathcal{A}_p'$ with increasing levels of detail. Let $\mathcal{D}$ denote the set of network designs and let $y_a(d)$ for $d \in \mathcal{D}$ be an indicator that denotes whether arc a is selected as platooning arc in design d ($y_a(d) = 1$) or not ($y_a(d) = 0$). Furthermore, let q_{ad} denote the number of trucks traversing arc a as part of a platoon in design d in any of the analysis scenarios.

The simplest score counts the number of times an arc a is selected as platoon lane arc across all designs.

Count: $n_a = \sum_{d \in \mathcal{D}} y_a(d)$.

Instead of simply counting the number of times an arc has been selected as platooning arc across the designs, we can look at the number of platoons that use an arc across the designs and the scenarios. Furthermore, we should recognize that platooning across a longer distance is more valuable. This gives a weighted count.

Weighted count: $w_a = \sum_{d \in \mathcal{D}} c_a \cdot q_{ad}$.

Both count and weighted count ignore the fact that a truck may have to deviate from its shortest path from origin to destination to benefit from platooning. Our next score seeks to remedy this omission by performing a more detail analysis of the savings that can be allocated to a truck in a platoon on a particular arc.

Let $SP(k)$ be the cost of using the shortest path between origin o_k and destination d_k for truck $k \in \mathcal{K}_s$. Recall that $\mathcal{K}_s$ is set of all trucks in scenario s. Furthermore, let $C(k, d)$ be

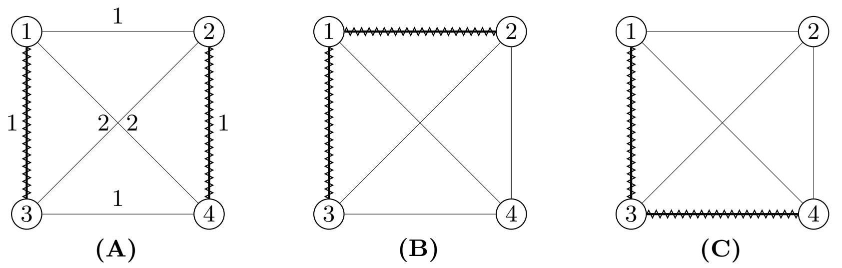


Figure 4.2: Three network designs from the generate step; bold zigzag - platoon lane; numbers indicate lengths of arcs

Truck	OD pair	SP costs	Design A		Design B		Design C	
			Route	Costs	Route	Costs	Route	Costs
p	(1,4)	2	1-2-4	1.9	1-3-4	1.9	1-3-4	1.8
q	(2,3)	2	2-4-3	1.9	2-1-3	1.9	2-1-3	1.9
r	(3,4)	1	3-4	1	3-4	1	3-4	0.9

Table 4.1: Routes and costs from the analyze step of network designs in Figure 4.2

the cost of the actual path of truck k in design $d \in \mathcal{D}$. We can then compute the savings associated with truck k as $\rho_k = \sum_{d \in \mathcal{D}} (SP(k) - C(k,d))/SP(k)$. Let $\mathcal{K}(a)$ denote the set of trucks using arc a as part of a platoon across all designs and across all scenarios $s \in \mathcal{S}_a$. This gives us the implied savings.

Implied savings: $i_a = \sum_{k \in \mathcal{K}(a)} \rho_k \cdot c_a$

Note that it is also possible to adjust the weighted count and the implied savings to reflect any difference in the overall performance of the network designs. However, preliminary computational experiments did not show any benefit of doing so.

To illustrate how to compute the different scores, we present a simple network example with three designs in Figure 4.2. Consider an analysis scenario with three trucks p, q, and r, with OD pairs (1,4), (2,3), and (3,4). Let the fuel savings factor ρ be 0.9. Table 4.1 specifies the least-cost routes for all trucks for each design.

Using this information, we compute the different scores that are shown in Table 4.2. For instance, arc 2-4 has a 'count' score of 1 since it appears in one of the three designs (A). Its 'weighted count' score is 2 as trucks p and q use it to platoon in design A. Similarly, calculating the 'implied savings' score for trucks p and q by comparing the costs of their shortest paths and actual costs in design A gives us a value of 0.1.

We see that all scores indicate that arc 1-3 is the most valuable arc but the more sophisticated methods disqualify arc 1-2 since it is not used for platooning.

Arc	Count	Weighted count	Implied savings
1–3	3	4	0.25
2–4	1	2	0.1
1–2	1	0	0
3–4	1	2	0.1

Table 4.2: Scores for different platooning lanes from all example designs in Figure 4.2

4.3.3 Blend

Rather than designating the best performing network design (out of the M network designs) as our platoon lane network design (as is done, for example, in Sample Average Approximation (Kleywegt et al., 2002)), we use the arc scores to blend the network designs, i.e., we identify and combine the most valuable platoon arcs into a blended design.

The reason for not simply selecting the best performing network design is that each of the M network designs was generated using only a small number of generation scenarios, and that therefore there is likely potential for improvement.

The rationale for blending network designs is the following. When using only a few scenarios in an instance of PLNDP, the representation of the demand uncertainty is not as accurate as when using many scenarios. As a consequence, the resulting network design may not be as good. That is, the network design may have some "good" parts, but also some "not so good" parts. By blending designs, we seek to extract the "good" parts of network designs and use these to construct a single high-quality design. We draw some inspiration here from the field of genetic algorithms where a candidate solutions are altered or evolved towards better solutions (Mitchell, 1998).

Based on the computed scores from analyze step, we select the (platooning) arcs to form a blended design that maximizes the total value. Here, we present two approaches for doing so: a greedy heuristic and an integer program. Although a greedy approach can be considered "rough", it can sometimes produce robust solutions in uncertain settings (Powell et al., 2000).

Greedy. First, we sort arcs $a \in \mathcal{A}'_p$ in decreasing order of their scores. Starting from the arc with the highest score, we select arcs to be platooning arcs in the final design until the budget has been exhausted.

Integer programming. The advantage of using an integer program over a greedy approach is that we can find the optimal set of arcs given their scores and the budget. Let s_a be the score of arc a and let x_a be 1 if arc a is chosen to be a platooning arc in the final design and 0 otherwise. The integer program to blend is the following (a binary knapsack problem)

$$\max \quad \sum_{a \in \mathcal{A}_p} s_a \cdot x_a \tag{4.15}$$

$$\sum_{a \in \mathcal{A}_p} f_a x_a \leq B \tag{4.16}$$

$$x_a \in \{0,1\} \qquad \forall a \in \mathcal{A}'_p \tag{4.17}$$

The objective function (4.15) maximizes the total score. Constraint (4.16) sets the maximum budget. Constraints (4.17) specify the domains of the decision variables.

Putting together the different scoring and selection procedures gives six different blending methods.

4.4 Numerical experiments

In this section, we evaluate the efficacy of our methods based on computational experiments with different instances. We solve the PLNDP M times for N random *generation* scenarios. For 20 random scenarios, we consider different combinations of N and M, i.e., $(1,20)$, $(5,4)$, $(10,2)$, and $(20,1)$. We evaluate each of the M designs on 100 random *analysis* scenarios and use the methods from Section 4.3.3 to blend designs. To evaluate the performance of the *final* combined designs, we use 100 random *testing* scenarios that were not part of the generation or analysis sets. We implemented these experiments in Python 3.6.3 with Gurobi 7.0 (Gurobi Optimization, LLC, 2021) as the IP solver on an Intel i7-6820HQ machine with a 2.70Ghz processor and 24 GB RAM.

4.4.1 Description of the instances

We generate instances on the German highway network. Figure 4.3 shows the network consisting of 20 of the largest cities represented by nodes and 44 road segments by edges. The weights of the edges represent the travel costs between two cities and are proportional to the real distances (Google maps). The sum of all distances in the network is 8221km. Trucks travel at a constant speed of 80 km/h.

We vary the spatial and temporal characteristics of the truck trips to create four sets of instances in total. In the UNI instances, each city is equally likely to serve as an origin or a destination. In the OD instances, eight cities (Bremen, Cologne, Dresden, Hamburg,

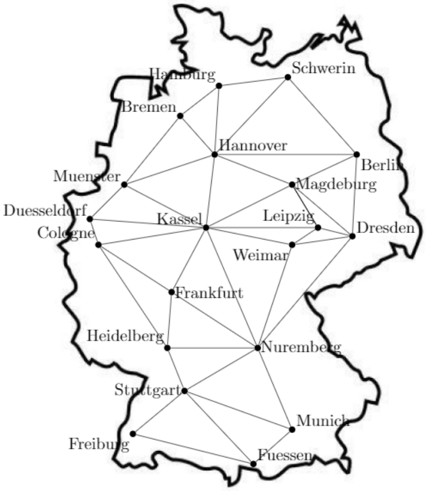


Figure 4.3: Representation of the German highway network

Hannover, Kassel, Munich, and Stuttgart) are twice as likely to serve as an origin or destination. These represent supply chain hubs. With regards to the departure and arrival time windows, we generate a deadline for each city destination of 21:00 or 22:00 across all scenarios. This deadline could relate to the cut-off time for containers to be loaded on a vessel or the closing time of a certain supply chain facility. We generate two sets of departure time instances. In one set of instances, labeled Fixed Flexibility (FF), all truck trips have a departure time flexibility of one hour. This means that each truck trip has an *earliest departure time* that is one hour before the *latest departure time*. If the truck leaves at the latest departure time, it arrives at the destination at the deadline taking the shortest path from origin to destination without any en-route waiting. In another set of instances, labeled Variable Flexibility (VF), trucks can depart at a random time between 05:00 and the latest departure time. This (possibly) gives trucks some flexibility to wait for other trucks or make detours to meet with other trucks to form platoons. All together, this gives four sets of instances, i.e., UNI-VF, UNI-FF, OD-VF, and OD-FF.

In our initial set of experiments, we generate instances with 40 truck trips. We assume that the costs to add a platoon lane are proportional to the distance of the arc. As a platoon lane budget B, we consider a maximum of 25% of the total distance of the network.

4.4.2 Impact of number of scenarios

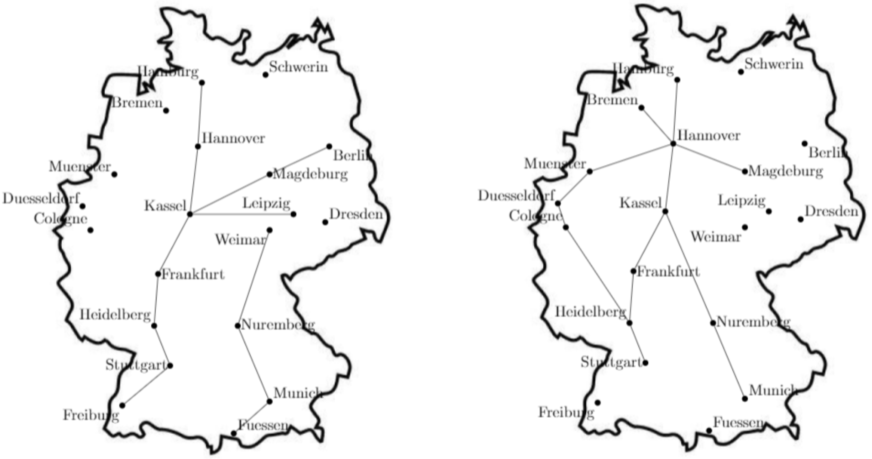
In Table 4.3, we report the percentage savings as compared to the setting without platooning. We also report the percentage of trucks in a platoon, i.e., the percentage of trucks that

Instance	(N,M)	GENERATE			ANALYZE	
		% savings	% trucks in platoon	Run time (s)	% savings	% trucks in platoon
OD-FF	(1,20)	4.40	59.63	2.37	1.32	44.49
	(5,4)	3.71	53.50	20.03	1.44	48.12
	(10,2)	3.63	50.75	46.50	1.48	48.05
	(20,1)	3.57	52.25	145.68	1.54	48.50
UNI-FF	(1,20)	3.85	60.63	2.75	1.05	41.10
	(5,4)	2.89	46.38	22.28	1.11	42.29
	(10,2)	2.83	52.13	61.97	1.33	48.53
	(20,1)	2.76	52.50	162.68	1.31	50.80
OD-VF	(1,20)	5.12	70.88	26.03	1.68	43.95
	(5,4)	4.42	64.38	430.28	1.89	45.10
	(10,2)	4.35	60.75	5146.02	1.61	45.25
	(20,1)	4.28	64.13	15327.30	2.01	49.30
UNI-VF	(1,20)	4.84	69.87	17.77	1.45	43.59
	(5,4)	3.92	52.75	484.05	1.32	39.76
	(10,2)	3.75	61.88	7079.00	1.74	48.40
	(20,1)	3.63	57.75	50054.64	1.41	47.45

Table 4.3: Platoon savings averaged over 100 testing scenarios for different number of scenarios

uses at least one platoon lane on their route. We report both the ‘generate’ and the ‘analyze’ results where the latter are the ‘out-of-sample’ results by solving the platoon routing problem for the analysis scenarios that were not used in the generate step. Table 4.3 also includes the generation run times. All values are averaged over all scenarios and repetitions.

As expected, we see higher savings for the generation scenarios than for the analysis scenarios. This is because the objective value of the optimization does not accurately incorporate the full uncertainty, especially when using a small set of generation scenarios. As the analysis scenarios are different from the generation scenarios, not all possible realizations have been explicitly considered in the generate step. We see that the difference in performance is less for the setting in which we use more scenarios. While the ‘in-sample’ savings decrease when using more scenarios, we see a better performance on the ‘out-of-sample’ analysis scenarios. With more scenarios, the generated design is not catered to one specific setting and is therefore more robust to a wider variety of scenarios. We see a similar trend for the percentage of trucks in a platoon. For all instances, this measure is significantly larger for the generation scenarios as compared to the analysis scenarios. Figure 4.4 shows an example of the different designs obtained for different numbers of scenarios. The design based on one single scenario in Figure 4.4a is quite different to the design based on 20 scenarios as seen in Figure 4.4b.



(a) 1-scenario design

(b) 20-scenario design

Figure 4.4: Example of designs with lower and higher number of scenarios

Based on the results in Table 4.3, we can also compare the impact of the spatial and temporal characteristics of the instances on the overall performance of the system. Consider the pair OD-FF and OD-VF, where the scenarios share the same spatial properties but differ in terms of the time flexibility of the truck trips. Since trucks can wait longer or make longer detours to form platoons in OD-VF, the reported savings are higher. We observe similar results when comparing UNI-FF and UNI-VF. Focusing on the spatial distribution, we see higher savings for the OD cases. Due to the geographical clustering of the origins and destinations, trucks can more easily find truck platoons with less detours.

Looking at the run times, we see a sharp increase with the number of scenarios especially for the cases with more departure time flexibility (VF). Incorporating more scenarios quickly leads to prohibitive run times and out of memory errors. In the following section, we present the results for several blending methods to improve the performance without including more scenarios in a single generate run.

4.4.3 Performance of the blending methods

To assess the performances of the different blending methods, we present the average percentage savings obtained from 100 random testing scenarios in Table 4.4. As an additional benchmark, we compare the performance of the blended design with the best individual design (BID) in terms savings in the analysis scenarios. Note that for the (20,1) case, the cells are empty as there is only one design generated, so blending is not possible.

Instance	(N,M)	Count		Weighted count		Implied savings		BID
		IP	Greedy	IP	Greedy	IP	Greedy	
OD-FF	(1,20)	1.71	1.71	1.71	1.71	1.71	1.71	1.56
	(5,4)	1.62	1.62	1.66	1.66	1.71	1.65	1.64
	(10,2)	1.60	1.61	1.72	1.72	1.72	1.72	1.72
	(20,1)	-	-	-	-	-	-	1.71
UNI-FF	(1,20)	1.35	1.30	1.31	1.36	1.32	1.38	1.22
	(5,4)	1.28	1.31	1.31	1.27	1.33	1.33	1.31
	(10,2)	1.33	1.29	1.29	1.29	1.33	1.33	1.31
	(20,1)	-	-	-	-	-	-	1.34
OD-VF	(1,20)	1.95	1.95	2.06	2.06	2.06	1.90	1.95
	(5,4)	2.02	2.02	2.02	2.02	2.02	2.02	2.02
	(10,2)	1.97	2.01	2.02	2.02	2.02	2.02	2.02
	(20,1)	-	-	-	-	-	-	2.02
UNI-VF	(1,20)	1.78	1.73	1.78	1.79	1.82	1.80	1.74
	(5,4)	1.51	1.77	1.81	1.83	1.79	1.83	1.81
	(10,2)	1.82	1.75	1.84	1.85	1.84	1.81	1.85
	(20,1)	-	-	-	-	-	-	1.83

Table 4.4: Platoon savings averaged over 100 testing scenarios for different blending methods

Overall, we see that the blending methods perform well. Blending multiple designs that were each created with less than 20 scenarios often outperforms the single design obtained by solving the network design problem with 20 scenarios. In fact, we see that even the blended 1-scenario designs show similar savings as the 20-scenario design. Recall from Table 4.3 that blending 20 1-scenario designs takes much less time than solving one 20-scenario design.

We also see that the blending methods perform well when compared to the best individual designs. For example, for the OD-FF instance we see that the blending methods for the (1,20) setting lead to savings of 1.71% (for all methods) while the best individual design leads to savings of 1.56%. This illustrates the value of blending different designs by extracting their different “good” parts. Moreover, we observe that taking the best individual design from a set of designs that each was generated with 4 or 10 scenarios appears to perform quite well, similar or better than the single 20-scenario design.

When we compare the results of the various blending methods, the difference are very small and there is no clear ‘winner’. For instance, all the 1-scenario blended designs in OD-FF result in the same average savings, equal to the 20-scenario BID savings. The differences remain small even when we look at the two steps - score and select - separately. Among the different score options, ‘savings’ and ‘implied savings’ appear to marginally outperform ‘count’ across all instances. This indicates that taking into account more detailed information on the usage of different platoon lanes in the score phase helps to improve the

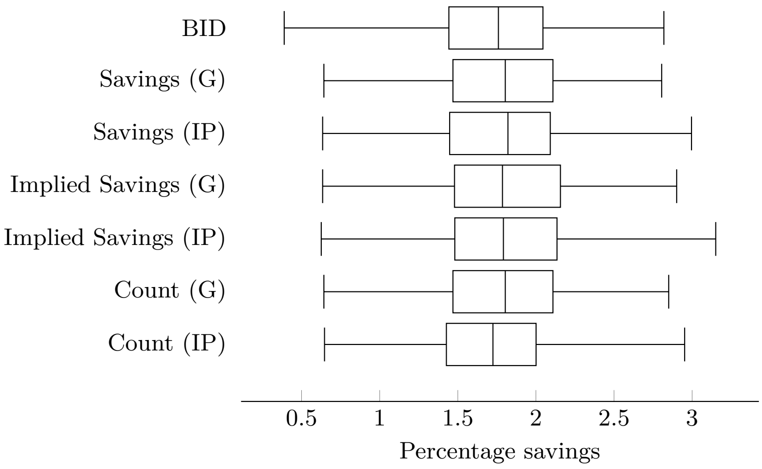


Figure 4.5: Boxplots showing variation in the performance of the blending methods for $(1, 20)$ UNI-VF

selection phase. The same is true when comparing the different select methods - greedy and IP. Both perform equally well on average. This indeed suggests that in a setting with a lot of uncertainty, an exact IP-based approach does not necessarily outperform a simple greedy approach.

To provide more insights into the variation of the results for the different methods, Figure 4.5 presents box plots for the $(1, 20)$, UNI-VF instance. We see that the minimum performance of all the blending methods is better than the performance of the best individual design. Moreover, the maximum performance of the blending methods is similar or better. The again highlights the potential benefits of blending different designs.

4.4.4 Impact of varying budget and number of trucks

The available budget and the number of truck trips are likely to impact both the performance of the network designs and the different blending methods. With a lower budget or fewer trucks, there will be fewer platoons lanes, and also a decreased possibility of finding platoon partners, which would both decrease platooning benefits. To study how pronounced this effect is, and how it impacts our methods, we vary these parameters. So far, we have used base case values of 25% for the budget and 40 for the number of trucks. In the next set of experiments, we also consider a budget of 10% and 10 trucks.

In Table 4.5, we report the average savings for the blended design using the ‘implied savings IP’ method for the different budget-truck combinations. We show only these results as we have seen that all methods perform equally well. We include two benchmarks, the

Instance	No of trucks	Budget	(1,20) blended	(1,20) BID	20-scenario
OD-FF	40	25%	1.71	1.56	1.71
		10%	0.90	0.93	1.01
	10	25%	0.47	0.43	0.50
		10%	0.27	0.30	0.21
UNI-FF	40	25%	1.32	1.22	1.34
		10%	0.80	0.76	0.85
	10	25%	0.41	0.37	0.41
		10%	0.31	0.21	0.25
OD-VF	40	25%	2.06	1.95	2.02
		10%	1.16	1.22	1.19
	10	25%	0.97	0.85	0.91
		10%	0.61	0.53	0.52
UNI-VF	40	25%	1.82	1.74	1.83
		10%	1.09	1.04	1.09
	10	25%	0.77	0.36	0.71
		10%	0.50	0.31	0.38

Table 4.5: Platoon savings averaged over 100 testing scenarios for various truck and budget parameters

$(1, 20)$ BID and the 20-scenario design. Again, we see that our blending method performs well as compared to the benchmarks. Across all instances, we see that blending designs is particularly beneficial for scenarios with fewer truck trips (i.e., 10). When there are fewer trips, there is more variation between the different scenarios. This means there is less (partial) overlap of potential truck routes between different scenarios. As a result, a design generated using one particular random scenario will likely not perform well when tested with another random scenario. Therefore, the $(1, 20)$ BIDs tend to perform worse than the blended designs in these cases.

Moreover, we also see that blending designs is more beneficial for instances with a larger budget (i.e., 25%). This could be because the larger budget allows more freedom to pick platooning lane arcs. When the budget is low, there may only be a few attractive arcs that are always selected as platooning lanes. With a large budget, there is probably more variation between designs for different scenarios and thus more room to carefully blend different designs.

4.4.5 Impact of ignoring time in the generate step

We introduced three steps to solve our network design problem, i.e., generate, analyze, and blend. The first step - generate - integrates the network planning and the platoon routing problem to come up with initial network designs. This step is computationally challenging and has relatively long solve times as seen in Table 4.3. One way to speed up the computation in the network design is by ignoring the time windows of the platoon routing part. This will not change the output of the generate step, i.e., the set of platoon lane arcs.

By ignoring the departure and arrival time constraints on the truck trips, we no longer need a time-expanded network in the problem formulation in Section 4.2.1. This means that we can drop index t from all variables. For instance, variable x_{ak}^{ts} now becomes x_{ak}^{s}, which takes a value of 1 if truck k travels on arc a as part of a platoon in scenario s.

Table 4.6 presents the percentage savings for the final design starting with the generate step with and without time. We use the implied savings IP approach to blend the designs. Note that we ignore time only in the initial design step. To allow for a fair comparison of the final designs, we evaluate all designs with the same 100 analysis scenarios, fully taking into account the timing of the trips in the route optimization.

Interestingly,the results suggest that ignoring time does not deteriorate the results. On the contrary, we see that we sometimes achieve better results when ignoring time in the first step. However, the differences in performance are small. One potential explanation for this is that designing a network involves selecting the most appropriate platooning lane arcs, which is fundamentally a spatial decision. With enough trucks that have reasonable flexibility and over multiple scenarios, the impact of time constraints are likely small. Moreover, detours associated with platooning tend to be quite small (Bhoopalam et al., 2020). As a result, even when we ignore time, the truck routes are not likely to be very different. Note that ignoring time does drastically reduces solve time. Average run times across different (N,M) variants reduce from 4940 to 15 seconds. For UNI-VF (20,1) we can solve the design problem in 46 seconds instead of 50,000 seconds.

Next, Table 4.7 shows the results on the random testing scenarios for different values of budget and number of truck trips. The table again shows that the results for the cases with and without time are very similar. This suggests that both approaches produce nearly identical designs. In some cases, designs generated by neglecting time even perform marginally better. The geographical aspect of network design seems to dominate. Overall, the results indicate that simplifying the initial design problem still produces good network designs within our blending framework.

Instance	(N,M)	Time	No-time
OD-FF	(1,20)	1.71	1.71
	(5,4)	1.71	1.72
	(10,2)	1.72	1.67
	(20,1)	-	-
UNI-FF	(1,20)	1.32	1.36
	(5,4)	1.33	1.34
	(10,2)	1.33	1.34
	(20,1)	-	-
OD-VF	(1,20)	2.06	2.06
	(5,4)	2.02	2.02
	(10,2)	2.02	2.13
	(20,1)	-	-
UNI-VF	(1,20)	1.82	1.82
	(5,4)	1.79	1.82
	(10,2)	1.84	1.81
	(20,1)	-	-

Table 4.6: Platoon savings averaged over 100 testing scenarios when ignoring time in initial network generation

Instance	40 trucks				10 trucks			
	25% budget		10% budget		25% budget		10% budget	
	Time	No time	Time	No time	Time	No time	Time	No time
OD-FF	1.71	1.71	0.90	0.93	0.47	0.51	0.27	0.28
UNI-FF	1.32	1.36	0.80	0.85	0.41	0.38	0.31	0.30
OD-VF	2.06	2.06	1.16	1.16	0.97	0.93	0.61	0.61
UNI-VF	1.82	1.82	1.09	1.09	0.77	0.83	0.50	0.53

Table 4.7: Platoon savings averaged over 100 testing scenarios when ignoring time in initial network generation

Instance	40 trucks				10 trucks			
	25% budget		10% budget		25% budget		10% budget	
	With generate	Skip generate	With generate	Skip generate	With generate	Skip generate	With generate	Skip generate
OD-FF	1.71	1.72	0.90	0.97	0.47	0.49	0.27	0.27
UNI-FF	1.32	1.31	0.80	0.80	0.41	0.40	0.31	0.30
OD-VF	2.06	2.06	1.16	1.05	0.97	0.96	0.61	0.53
UNI-VF	1.82	1.75	1.09	1.05	0.77	0.71	0.50	0.49

Table 4.8: Impact of skipping the generate step - average testing savings from blended (1,20) designs using implied savings IP

4.4.6 Impact of skipping the generate step

In the previous set of experiments, we have seen that simplifying the network design problem in the first step can reduce computational efforts. In this section, we go further by completely skipping the initial network generate step. Instead, we start the analysis phase with a network in which all arcs represent platooning lanes. This ‘design’ is not feasible with respect to the budget but is only used to assess the value of each arc in the network. We do this by solving the PRP for the 100 analysis scenarios and subsequently scoring the different arcs based on the associated implied savings. We use these scores to build a budget-feasible design by solving the IP for our selection step. These final designs are then tested with 100 testing scenarios. Table 4.8 shows the results. As a benchmark, we also present the results for the base setting that includes the initial generate step.

For the 25%, 40 truck cases, we see that the results when skipping the generate step are similar to the results when running the generate step. A potential reason for this is that with a reasonable number of trucks and budget, the design step may be less critical as there is enough flexibility to find good platoons. In contrast, we see that for the instances with less budget and fewer trucks, there is value in careful optimization as there is more room for error.

We also observe that the designs generated by skipping generate never perform better in the VF instances. This could be due to the larger time flexibility of the truck trips in these instances. Their departure times can vary widely, which again means that careful planning and optimization is necessary to find and form platoons. This is not so much the case for the FF cases since trucks depart closer to each other and can more easily find platoon partners.

4.5 Concluding remarks

In this paper, we propose new methods to incorporate uncertainty in long-term infrastructure design decisions. We apply these methods in the context of planning dedicated lanes for truck platooning. Dedicated platooning lanes can help the safe and effective deployment of truck platoons. We particularly focus on determining where in the network to best install platooning lanes given a certain budget. We formulate the Platoon Lane Network Design Problem (PLNDP), where we use scenarios to model the uncertainty in truck flows. While a large number of scenarios is likely to lead to better solutions, it can create computational challenges. To deal with this, we present methods to blend designs obtained from solving the PLNDP multiple times, each with few scenarios. Our numerical experiments on instances based on the German highway network showed that our blending methods perform well.

We see several promising avenues for future research based on the ideas proposed in this paper. First, it is interesting to study how to apply the 'blending' concept to other complex settings that involve decision making under uncertainty such as automated vehicle network design, bike path allocation, time slot assignment and urban infrastructure related to water, energy, and communication. While the general concept is likely to apply, further research is needed to develop scoring and blending approaches tailored to these specific contexts. Second, a fundamental open question is how much detail about the operational problem needs to be taken into account in strategic planning problems to generate good solutions. Our results suggest that good solutions can be achieved without considering too much detail but it is important to better understand the underlying mechanism of this observation.

5 The long road to automated trucking: Insights from driver focus groups

5.1 Introduction

Rapid developments in automotive technologies continue to advance the realization of autonomous vehicles. Several semi-autonomous features such as cruise control, parking assist, and lane-keeping assist have become commonplace (Yang & Coughlin, 2014) while companies like Tesla offer more advanced features like autopilot (Tesla, 2021). Tests with fully autonomous or self-driving vehicles are well underway. A recent overview by CB Insights (2020) reports the progress of over forty companies making inroads in this space.

Autonomous vehicle technology gives rise to several potential benefits. By eliminating human error and inconsistencies, it is likely that autonomous vehicles will elevate safety levels and improve traffic flow (Gruel & Stanford, 2016). They can possibly increase "equality in mobility" by allowing groups such as the physically challenged and the aged to make use of cars. Moreover, they free up time for commuters to carry out additional tasks (Pudāne et al., 2019). Apart from these direct benefits, self-driving vehicles could change society in more fundamental ways. For instance, self-driving cars could adopt a sharing model and operate as "driverless taxis" eliminating the need for car ownership (Combs, 2019; Masoud & Jayakrishnan, 2016). Not only would such a system reduce the total number of cars, but it would also free up space in central urban areas by not requiring parking spaces. Milakis et al. (2017); Gruel & Stanford (2016) outline such ripple effects of self-driving vehicles. Unsurprisingly, Brynjolfsson & McAfee (2014) often refer to autonomous vehicles as an important element of what they call the "second machine age".

As with any such potentially paradigm-shifting development, a gradual and phased deployment is likely. Freight transport, more specifically, commercial trucking is often thought of as one of the most interesting early application areas for various reasons. First, there already exist successful implementations of autonomous vehicle technology in closed settings such as in warehouses or container terminals (Azadeh et al., 2019; Roodenbergen & Vis, 2001; Kim & Bae, 2004). Second, they reduce operating costs and increase hours of service leading to direct business savings for commercial fleet operators (Fritschy & Spinler, 2019). Companies have therefore begun developing and testing self-driving trucks (Hirsch et al., 2020; Frangoul, 2019; Tesla, 2019; Benz, 2015).

Despite the enormous investments, it is unlikely that autonomous trucks will be allowed on the road any time soon. Several safety concerns remain along with questions about security, privacy, and liability (Simpson et al., 2019; Fagnant & Kockelman, 2015). Consequently, legal and policy issues continue to exist (Slowik & Sharpe, 2018). Therefore, driver supervision would likely still be needed in the near future. Further progress in technology and testing would gradually reduce this requirement.

With cruise control and lane-keeping assist commercially available, further progress in technology points to platooning as the next step. Platooning is often seen as one of the most likely first steps in the roll-out of automated driving on public roads (World Maritime University, 2019). Platooning technology virtually connects a set of trucks to form a convoy with a leading truck and one or more following trucks at short headways. Following trucks may automatically manoeuvre based on the operation of the lead truck. With time and progressing technology, we may see platoons with drivers resting while being in the truck or even platoons in which not all trucks require drivers, thereby moving closer and closer to a society with fully autonomous self-driving vehicles (Kilcarr, 2016). Various companies have conducted real life tests in different parts of the world (Eckhardt et al., 2016; Ministry of Transport - Singapore, 2017; Tsugawa, 2014).

Truck platooning and related automotive technologies will change the job of truck drivers by gradually taking over more and more tasks. Truck drivers' acceptance of these developments is important not only for the future of platooning but for that of automated driving in general. An implementation of this technology without considering driver views could leave them feeling disgruntled (Brown et al., 2002), slowing down the adaptation of automated driving in the process. The abundance of literature on technology acceptance in many areas shows the necessity of such research. We provide a brief overview of this literature stream in Section 5.2. The current driver shortages only increase the importance of exploring drivers' anticipation of this new technology, and their views on how it would affect their job (satisfaction). (Müller, 2020; Costello & Suarez, 2015)

In the platooning literature, most work has done been from the perspective of technology (Bergenhem et al., 2012a; Maiti et al., 2017), safe manoeuvring of platoons (Kavathekar & Chen, 2011), human factors (Heikoop et al., 2017; Hjamdähl et al., 2017; Larburu et al., 2010)) and transportation optimization (Bhoopalam et al., 2018). A few research efforts such as Castritius et al. (2020b); Yang et al. (2018); Fröhlich et al. (2018); Richardson et al. (2017) look at driver acceptance of platooning technology focusing on the first phase of deployment in which drivers still need to be present and attentive in all trucks of the platoon. However, the potential benefits of this first phase in terms of cost savings appear to be small in practice (Daimler, 2019). Therefore, we go beyond simple platooning and consider more advanced forms of vehicle automation in which drivers in the following trucks may rest or in which drivers are not needed in the following trucks. In the latter setting, there is only a driver in the first truck of the platoon. These more advanced forms clearly have a big impact on the work of the truck drivers, creating a need to understand their acceptance of such more radical technological change.

To the best of our knowledge, we are the first to study driver acceptance of these more advanced forms of autonomous driving technology and platooning. Given this gap, we look at these developments from an open-ended and exploratory perspective. We believe the lack of knowledge in this domain precludes any more specific quantitative or theory testing research. Therefore, we aim to open the pathway towards more concerted, quantitative, and confirmatory research efforts in the area and consequently contribute toward the implementation of automated driving. More specifically, our contribution is twofold - (i) we explore the various perceptions of drivers on the different forms of truck platooning and (ii) we explore the range of driver perspectives regarding the advantages and disadvantages of the different forms of truck platooning for their jobs.

The rest of the chapter is structured as follows. In Section 5.2, we review the technology acceptance literature with a focus on transportation. Following this, we explain our research methods and data collection in Section 5.3. Then, we go into our findings in Section 5.4 and discuss these findings in Section 5.5. We conclude the chapter in Section 5.6.

5.2 Relevant literature

There is a large body of literature on technology acceptance. The basic framework most often used to study the acceptance of a new technology is the *Technology Acceptance Model (TAM)* developed by Davis (1989). Several studies like Marangunić & Granić (2015); Bagozzi (2007); King & He (2006); Ma & Liu (2004); Lee et al. (2003); Szajna (1996) provide extensive overviews of TAM research. Our current work could inform and assist in the design of more specific TAM research for the advanced platooning forms.

The digitization and automation of work has received a lot of attention. The acceptance of information systems technology has been studied in multiple contexts such as office automation (Marquié et al., 1994; Hardin, 1960a,b), sales (Buttle et al., 2006; Morgan & Links, 2001), healthcare (Ziefle & Valdez, 2017; Pino et al., 2015; Hu et al., 2015; Pai & l Huang, 2011; Wilkowska & Ziefle, 2011; Walter & Lopez, 2008), education (Park & Han, 2016; Al-Emran et al., 2018; Almaiah, 2018). Moreover, there is a large stream of research that focuses on industrial automation - for instance, in domains of automobile manufacturing (Faunce, 1960), power plant operation (Mann & Hoffman, 1960), and industrial production (Haddad, 1996; Walker, 1957). In this context, Argote et al. (1983) and Haddad (1996) point out that technology could reduce social interactions and level of autonomy in a job, potentially leading to alienation and stress.

In transportation, most technology acceptance research focuses on passenger and private transport. This includes automated public transport (Madigan et al., 2017; Alessandrini et al., 2014), bicycle sharing (Fan & Zheng, 2020; Kaplan et al., 2015), and even air travel (Rice et al., 2019; Bouwens et al., 2018). When it comes to private vehicles, acceptance research began growing in prominence in the early noughties and has been progressing alongside the technology - with earlier studies looking at advanced driver assistance systems like cruise control and speed assist (Wiethoff et al., 2002; Marchau et al., 2001) to more recent studies looking at self-driving cars (Raue et al., 2019; Robertson et al., 2017; Daziano et al., 2017; Schoettle & Sivak, 2014); see Becker & Axhausen (2017) for a literature review.

In contrast, the body of literature focusing on commercial drivers is smaller and more recent. Ghazizadeh et al. (2012) find that trust in technology is a major determinant in drivers' willingness to use on-board monitoring systems. Similar conclusions are drawn by Richardson et al. (2017) who also point out that drivers are afraid of being made redundant. As indicated in Section 5.1, a handful of studies look at the first phase of platooning technology, where drivers in all trucks need to be present and attentive at all times. Neubauer et al. (2019); Fröhlich et al. (2018) both encounter skepticism from drivers for reasons similar to those pointed out by Richardson et al. (2017). Castritius et al. (2020b); Yang et al. (2018) take an additional step and check acceptance of drivers before and after they have experienced platooning technology. They find drivers to be more open and accepting after having experienced working with the technology.

5.3 Research methods and design

Our research focuses on an emerging technology that has not received much attention from the truck driver perspective. As a result, it is not clear how the people that have to work with the new technology perceive and evaluate the developments. Focus groups are a suitable method of data collection in such exploratory settings (Sutton & Arnold, 2013).

The group dynamic among participants in a focus groups fosters the generation of new ideas that might not have been thought of previously or otherwise, even by the researcher (see Morgan (1996); Kitzinger (1994, 1995)). This may help participants shape their ideas during the discussion and, as a result, contribute more meaningfully. Moreover, the open ended nature of focus groups ensures that the researchers' preconceived notions do not bias the outcomes. Furthermore, gathering information from participants in focus groups is more time-efficient compared to one-on-one settings such as interviews.

Focus groups are a common research method in technology acceptance research (Ziefle & Valdez, 2017; Park & Han, 2016; Pino et al., 2015; de Barcellos et al., 2014; Zaunbrecher et al., 2014; Wilkowska & Ziefle, 2011) and in transportation (Pudāne et al., 2019; Maréchal, 2016; Simons et al., 2014, 2013; Coughlin, 2001; Yassuda et al., 1997). Prior interviews often help in structuring and designing focus groups (Sutton & Arnold, 2013). Therefore, we use a combination of interviews and focus groups in our study.

5.3.1 Research design

During the research design, we conducted semi-structured interviews with several experts from a Dutch research consultant group involved in managing national platooning projects such as CATALYST (Janssen et al., 2020) and ENSEMBLE (Ensemble, 2018). We structure the focus group design around the different levels of automation and associated involvement of drivers based on Bhoopalam et al. (2018). We briefly describe them below -

> **Human driven platooning (HDP).** All drivers in a platoon are required to be attentive at all times. The drivers in the following trucks receives assistance in the operational tasks such as braking and/or steering tasks but is still in control of the tactical driving tasks such as determining when to change lanes, turn or use signals etc.
>
> **Human driven platooning with in-platoon resting (HDP-IP).** Drivers in the following trucks may rest during the platoon as the following trucks can handle all driving tasks. This could mean that the time as part of the platoon does not count as formal driving time for the driver in the following trucks.
>
> **Hybrid platooning (HP).** This type of platooning allows the removal of drivers from one or all the following trucks in a platoon. Drivers would still need to be present when a truck is outside of the platoon. Therefore, drivers may need to be shuttled around between meet/split points of platoons to drive individual trucks to/from these points.

Existing platoon literature that we described in Section 5.2 focuses on HDP. We also consider the platooning forms associated with more advanced levels of automation. Table 5.1 provides an overview of the questions used in our focus groups. The questions are grouped into several categories. The first category serves as an introduction and is meant to get an idea of how drivers perceive their jobs and the way that any recent technology has changed their work. The following three categories correspond to the different forms of platooning. The questions across the different categories are mostly consistent with HDP and HDP-IP having some additional specific ones related to their respective characteristics. To conclude, participants were asked how they thought platooning technology would affect transport companies.

5.3.2 Recruitment and data collection

As is common in focus group research (see Wilkinson & Silverman (2004)), we conducted five focus groups in total. These focus groups took place in the Netherlands in the period between May 2019 and February 2020, i.e., before the Coronavirus pandemic. Each focus group had 4 to 7 truck drivers with a total of 25 drivers across the groups; 24 males and one female. The drivers had an average age of 46.2 years with the oldest being 63 and the youngest

Introduction
Who are you and what is your job?
What does your typical day at work look like?
Have you had to get used to any new technology at your job? How did it make your job different (easier/harder)?
Human driven platooning
Do you think this will become a reality? When?
Let's say it does become a reality. How would it affect the way you do your job?
What do you think the benefits of this are for you?
What are the drawbacks of this for you?
Human driven platooning with in-platoon resting
Do you think this sort of platooning will become a reality? If so, when?
How will this further development in the technology affect the way you do your job?
What do you think the benefits of this are for you?
What are the drawbacks of having this for you?
How would you like the truck cabin interior to be if you had to take a break in it?
Apart from taking breaks, what kind of other activities do you think you could do in a following truck?
Hybrid platooning
Do you think this sort of platooning will become a reality? If so, when?
How will this further development affect the way you do your job?
What do you think the benefits of this are for you?
What are the drawbacks of having this for you?
In such a scenario, would you prefer being the leader of a platoon or someone that mainly does first/last mile trips?
Final thoughts
How do you think platooning will affect your company if it does become a reality?

Table 5.1: Focus group questions

25. The drivers worked for different transport companies and transported different loads, e.g., containers, bulk or garbage. Some drivers only performed transportation trips within the Netherlands while others performed longer international trips. None of the drivers had any prior experience with platooning technology. We provide information on these drivers in 5.7.1. The focus groups had an average duration of approximately 75 minutes with the longest one taking 90 minutes.

To carry out these focus groups, we visited three truck stops in the Netherlands; at the Port of Rotterdam, in Vuren, and in Vlaardingen. In particular, we visited truck stops with restaurants where truck drivers spend their evenings after their work day. We approached truck drivers and asked if they would be willing to participate in our focus group. With sufficient participants, we carried out the focus group session. There were two visits in which we did not succeed in recruiting enough truck drivers to form a focus group.

During the focus groups, the participants were shown slides explaining each form of platooning and were allowed to freely express their thoughts with the moderator guiding the discussion and keeping all participants involved. The focus groups were all carried out in Dutch.

5.3.3 Data Analysis

The audio from all focus groups was recorded, transcribed, and translated to English for analysis. We studied the data using content analysis (Neuendorf & Kumar, 2015). That is, the data from all focus groups was coded and patterns were identified to gain insights. Like Pudāne et al. (2019), our analysis is largely inductive but with some deductive elements based on insights from the literature.

5.4 Findings

We now go into the findings from our focus groups. Findings will be accompanied by quotes from drivers where relevant.

5.4.1 Job satisfaction

In general, the drivers were proud of their work and felt that it brought them fulfillment. The drivers find it attractive to be on the road for long periods of time. While on the road, they especially appreciate their perceived freedom and autonomy. Furthermore, they find their jobs to be eventful as they move between different locations and meet different people along the way. These findings are consistent with earlier studies on truck driver job satisfaction (Johnson et al., 2011; Stephenson & Fox, 1996). Several drivers argued that it was hard to explain the joys of their work to someone outside the profession.

"I like everything [about the job] but I don't really know why. You grow up with it. It is just your thing. It is your life" (Rudy)

"It [truck driving] is a hobby for me." (John)

"You should see it [truck driving] as a hobby, otherwise it won't work." (Jan)

Viewing the profession as a hobby was seen as a necessity by drivers in order to deal with the negative sides of the job. The above mentioned positives often come with caveats such as being away from home and by yourself for extended periods or constantly having to deal with traffic. Traffic related frustrations include the 'anti-social' driving behavior of surrounding civilian traffic, that is, car drivers do not consider the sheer mass of a truck and treat it as just another car that can brake quickly when, for instance, a car would abruptly change lanes in front of them. As a result, nearly every truck driver had experienced some close calls on the road. The recently rising traffic levels have exacerbated this.

"And what I find very annoying at work is antisocial driving behavior. Selfish driving behavior. Just people who always want to get past a traffic jam. Then they are at the wrong place" (Robert)

"How people feel about you. That people have absolutely no respect for you on the street" (Shawn)

Apart from traffic concerns, drivers felt their jobs negatively impacted their social lives. Their jobs did give them the chance to meet other drivers and employees at the various locations they visited but it did take away the time with friends and family. These factors for dissatisfaction are in line with studies exclusively looking at truck driver job satisfaction in different parts of the world such as the United states (Fields, 1998; Mittal et al., 2018), China (Jiang et al., 2017), India (Mittal et al., 2018), the Netherlands (De Croon et al., 2002).

Some of the more recent job-related concerns were about the decrease in autonomy and freedom mainly due to recent developments in technology, which leads us to the next section.

5.4.2 Experiences with new technology

One of the technologies that has had the most profound impact on the work of the truck driver over the last two decades is the tachograph. A digital tachograph continuously tracks speed, driving periods, and breaks. For many drivers in our focus groups, the introduction of the tachograph represented a significant shift from the days when employers could only reach them on fixed telephones at certain locations. As employers constantly monitor the drivers, the drivers perceive less freedom and autonomy.

> *"But everything is planned exactly that way. It was not like this. They know that he [the driver] will arrive at this time and that he will be ready at that time. Everything is planned. The people are so focused and stressed, including the drivers, because they have to be exactly on time. That was not the case at the time."* (Adam)

Together with an on-board computer, many administrative tasks are now accomplished electronically which the drivers argue means that they have less social interaction.

> *"Now we no longer communicate [with people at drop-off location]. It is just click and press, we are no longer in contact. We don't really talk to each other anymore at the terminal. This [use the tachograph] is really all I do. This is the only time this whole week that I talk to someone."* (John)

Drivers have also get used to ABS (Anti-lock Braking System) and EBA (Emergency brake assist), which the overwhelming majority of the focus group drivers agreed was good and added to safety. In general, they felt that ABS did not fundamentally change their driving tasks. Some drivers however did not trust it since they felt it, on occasion, intervened at inappropriate times. This left them feeling they were not in control of the truck any more, and therefore unsafe.

> *"The system sometimes intervenes too quickly. I drove through Eindhoven on Monday and I was braking, gently braking. But it [EBA] did not not think it was hard enough. That thing just went off"* (Simon)

Another new technology that drivers mentioned was Adaptive Cruise Control (ACC). ACC in a vehicle automatically adjusts its speed to maintain a certain distance to the vehicle ahead. This is particularly relevant since platooning uses a more advanced version where all trucks are virtually connected. The majority opinion in the focus groups towards ACC seemed to be positive with drivers acknowledging it makes their tasks easier and safer.

> *"That is one great thing, that distance system [ACC]. You can just text while driving, now you can do everything. It couldn't be safer. You turn that thing on and you don't bump into anything"* (James)

The above quote indicates a possible unintended consequence of having ACC. Texting while driving is clearly unsafe and therefore illegal in the Netherlands (Ministry of Infrastructure and Water Management, 2019). The driving task with ACC demands less attentiveness from drivers leaving them room to focus on other tasks, which might have an adverse effect on traffic safety in certain sudden and unexpected situations (see Brookhuis et al. (2019)).

We now segue into the more specific discussions on platooning. We organize the following sub-sections based on the different forms of platooning.

5.4.3 Implementation of platooning

Citing the developments they have already seen and experienced, drivers believe that the different levels of platooning would make their way to public roads in the future. They did, however, have very different estimates on the expected timeline. A few drivers thought that the initial phases are already here - the trucks are just not virtually connected to each other. On the other hand, some other drivers, pointing to legal and regulatory processes, suggested it will take more than ten years before HDP would become a reality.

> *"And with that modern technology, that ABS, you actually already have that. You are all on the cruise control and that distance regulator. The car actually takes care of it. I think you are very much in the initial phase now."* (Harry)

> *"Yes, the system is already there, but I think it is still early. I think it will take 10-15 years. Then they are already a lot of steps further"* (Jay)

When it came to the timeline of HDP-IP, drivers thought it would appear about 5-10 years after HDP because of special infrastructure plausibly being required. Moreover, driving time regulations would need amending adding to the regulatory to-do list. The next step, HP was seen by drivers as something they would not experience since they would have retired by the time it would become a reality.

> *"This [HP] is absolutely going to happen. Whether we will experience it? - Let me put it this way, then we are really already 25 years in the future."* (Robert)

In the conversations about implementation, drivers also pointed out the usefulness of platooning would vary based on location - that is, platooning is likely to be implemented sooner in larger countries such as the United States or Australia. The longer distances there provide more opportunities for platooning. In smaller countries like the Netherlands, the distances between stops for trucks tend to be quite short, which means that the benefits are likely to be offset by the costs of forming a platoon. Furthermore, in a compact country like the Netherlands, the traffic tends to be denser with more interruptions from vehicles joining and leaving highways. As a result, the benefits of platooning here are likely to be lower. This is even more applicable to the more advanced forms – HDP-IP and HP– since longer distances are key for the benefits they provide.

> *" And we do not have those [long] distances. These [HDP-IP and HP] are very beautiful ideas. Hooking up hops. They have been busy with a system through the guardrail, but it does not work. I don't see this succeeding either."* (Martin)
>
> *"Plus, we're talking about one stop now. How many trucks are driving in the Netherlands that have at least 12-14 stops in a day."* (Martin)

Drivers also indicated that the achievement of a critical mass is essential for platooning to be a success, that is, it would work only if a lot of trucks are able to participate and collaborate. Drivers pointed out that a specific organization may need to manage the formation of platoons. This is similar to the idea of a *platoon service provider* (see Janssen et al. (2015))

> *Then you only get one transport company in the whole of the Netherlands or Europe that takes care of all trucks, because otherwise it [HP] is not possible. I cant just get on his truck, because I only have a permit for my company* (Daan)

5.4.4 Driving in a platoon in traffic

None of the drivers from the focus groups had prior experience of driving in a platoon. Citing the high traffic density in the Netherlands, drivers expressed their concerns about trusting platooning technology to handle some of the complicated traffic situations they have experienced. This is exacerbated by the "anti-social" driving behaviour of surrounding traffic. Drivers recounted instances of some of their close calls in traffic.

> *"On that specific trajectory [from the port to the highway] you are passing multiple exits. Basically all trucks that merge onto the highway are fully loaded. Since the road is elevated, the speed of the vehicles is low when they merge. How does this influence other road users? That's something to take into account. I would be uncomfortable on such points. That my truck is going to decide things."* (Rudy)

Some drivers however, did point out that if the technology would be reliable, it would lead to more relaxed driving - especially in a high traffic situations which can often be stressful. This was not the case with the more advanced forms of platooning. With HDP-IP, drivers found the idea of not being attentive and in control while being in the following truck hard to imagine. Given the repercussions of a potential accident, they would not be comfortable resting and posited that drivers should always be attentive.

> *"Surely you do not believe that I am going to sleep on a bed in such a moving thing [truck]. Well, certainly not."* (Adam)

> *"There is also the human aspect. You are in a convoy ten meters behind the truck in front of you, and you are going to close your eyes? No, you cannot do that."* (Simon)

HDP-IP introduces another dimension of trust. Drivers in the following trucks now need to trust the lead driver in addition to the technology, which they would find difficult to do. This was again because of the repercussions of a potential accident.

> *"Then you have to put your trust completely in the front driver. I have some trouble with that."* (Tim)

When it came to trusting technology, drivers preferred HP- driving the lead truck in such a platoon. This is because this would be closest to driving a truck the way they do currently, only with extra load at the back (in the form of follower trucks). They would not have to give away too much of their driving task to the system this way. One driver pointed out that this form of platooning makes most sense from the drivers' perspective since it eliminates all the qualms a following driver might face. They therefore suggested the previous forms of platooning be skipped. This is similar to the argument for skipping SAE level 3 in the context of automated passenger cars (see Auto2x (2019)).

For all forms of platooning, drivers said that it is important that trucks in a platoon are ordered correctly and safely. For instance, brake power and mass of a truck would determine how quickly it can stop in an emergency situation and a truck that can do so quicker best belongs at further behind in the platoon. Nowakowski et al. (2015) suggest having trucks in ascending order of engine power to mass ratio.

5.4.5 Effects of platooning on a driver's job

Drivers discussed how platooning could affect their jobs at length in the focus groups. Drivers expected to see many changes in their work days due to platooning. We structure these effects of platooning on their jobs into four interrelated categories - (i) pleasure/satisfaction of work, (ii) freedom/autonomy in their work, (iii) relationship with their employers, (iv) nature of tasks they perform.

(i) Pleasure/satisfaction of work - As we discussed in Section 5.4.1, many truck drivers truly enjoy their work. They viewed platooning as something that would negatively affect their work by making it more monotonous and less fun. As platooning technology takes over several driving tasks, it reduces the fulfillment of driving.

"I just want to drive, I want to drive myself. My passenger car is an automatic, I think that is very different in terms of technology, but I think in a truck I just like switching gears myself. Sure, I sometimes had a painful leg in the traffic jam and it is also more tiring, but on the other hand I think it is a lot nicer." (John)

"No, then it will be a very long and boring day. Then you have nothing to do" (Max)

(ii) Freedom/autonomy in their work - Being their own boss was something the truck drivers truly appreciated. Although recent developments in technology (see Section 5.4.2) have reduced the autonomy drivers perceive, they are still largely independent while on the road. Platooning, however, would further reduce their autonomy. Not only does it take over parts of their their driving tasks, but it also makes their driving schedules stricter. That is, drivers would have to follow tight guidelines to be able to meet up with other trucks to form platoons.

"You have even less control. And again a piece of freedom that you have to hand in." (Paul)

"And you are no longer your own boss. And then a computer will work with our machine. That does not make anyone happy. Every driver sitting here thinks this. You should not touch our machine. And I think that is the most important point. Then there is no more work for us." (Robert)

"We started working and we got the tachograph. Then we got a smarter tachograph and now we get an even smarter tachograph. We keep doing it because you can accelerate yourself. But when that is no longer there, there is really nothing left." (Daan)

As expected, this is aggravated by the increase in automation, that is, more advanced the form of platooning, the more freedom drivers lose. For instance, HDP-IP might cause drivers to even give up their traditional breaks for mandated ones in the truck. This would further increase their workloads. HP would imply that drivers must drive different trucks at different times, which means they have to give up their own personal truck. Being able to drive in their 'own' truck is very important for many drivers.

> *"Why would you want that [HDP-IP]? We already work an average of 13 hours a day."* (Andrew)

> *"Then you are in someone else's truck. Because that is still being ignored. It [our truck] is our house. You live in it all week and that [driving different trucks at different times] will not work."* (Yohan)

(iii) Relationship with their employers - Drivers opined that their employers would enjoy the bulk of platooning benefits as it reduces costs. In addition, drivers expressed concerns that employers would not value their work the same anymore, that is, employers may argue that the drivers now work less since the technology takes over a big portion of the driving task. As a result, they were afraid that they may be paid less. Again, these concerns were more vocally expressed for the more advanced forms of platooning. As discussed, with HDP-IP, employers might ask drivers to work longer days without appropriate compensation. This sentiment, that 'freeing up time' would actually exacerbate stress and time pressure, echoes results from a focus group study held in the context of self-driving cars: Pudāne et al. (2019) found that travelers anticipated that when others (e.g. employers) would know that they could spend time working when driving, this would be taken advantage of at the expense of the traveler.

> *" Yes, so you would not come home at all anymore. And probably for less pay, because you work less according to the boss."* (Andrew)

In the case of HP, employers may claim that the time spent shuttling drivers around between the meet/split of platoons is not actually work and not compensate them for it.

> *"Because what will the boss say when the driver gets out of the car: I'm not going to pay you anymore. So that driver has to be driven to another place in a van. Those hours are not paid and then it is again at the expense of the driver."* (Robert)

(iv) Nature of tasks they perform - Drivers perform a variety of tasks during the day apart from driving - such as administrative work, loading or unloading etc. Platooning technology could shake up the proportion of time drivers spend on each of them - mostly the advanced forms which do not require the drivers attention at all times. HDP-IP would change the way drivers spend time in their trucks - they could take breaks but also engage in other tasks. This could be entertainment related such as watching movies, work related such as doing some administration work, or related to personal development such as following a course.

“Administration. Maybe you can put a planner on such a truck. You are you planning for each other. Saves office building again” (Grant)

“ Maybe you are going to study or something. But yes, you still have to pay attention.” (Gabriel)

The first quote above points to potential future business practices. Furthermore, drivers themselves could take on additional roles such as handling calls, planning, and so on (Glaeser, 2007).

HP would significantly change the way drivers spend time outside of the truck. Apart from having to be shuttled around, drivers may have to perform more loading and unloading tasks. When all the trucks in a platoon are headed to the same destination (or start at the same origin), drivers will likely be responsible for the unloading (or loading) of all trucks in question. Drivers were not enthusiastic about this eating into their time they spend driving since it is the activity they enjoy the most. This is in line with Wijngaards et al. (2019) who find drivers significantly prefer driving over pick up and delivery tasks.

“Then I will drive three trucks, but indeed if I have to unload three trucks, how much time do I spend driving back and forth?” (Andrew)

5.4.6 Effects of platooning on the trucking industry

Throughout the focus group discussions, drivers spoke out on how they thought platooning would affect their companies and the trucking industry. We briefly touched upon these ideas in the previous section while discussing the relationship of drivers with their employers. Drivers saw clear benefits of platooning for a trucking company and therefore were fearful of being taken undue advantage of. For a company, drivers thought there were clear (financial) benefits -

“It is cost effective and it will benefit a company. Less fuel, tires, brakes. So in that respect you could take advantage of it.” (Shawn)

As a result, they argued companies would push for it and others eventually follow. Platooning technology requires an investment giving larger trucking companies an opportunity to strengthen their hold on the market by offering cheaper services to clients. Smaller companies and independent truck drivers would suffer and could potentially be driven out of business.

"So as a small company you will lose the battle, because you will no longer accept it. Large companies may already have a lot of that [platooning] knowledge. That is how it is going to happen. As a small business owner, you will really lose this battle. I am convinced of that." (Daan)

"I think that small businesses of up to 40-50 trucks can all leave and that you will only count if you have around 100 trucks" (Paul)

Therefore, if left completely unregulated, drivers expected that larger and financially stronger trucking operators and logistics service providers would take over the industry.

5.5 Discussion

The findings suggest that truck drivers are generally not positive about the implications of platooning technology on their work environment. Broadly speaking, this is because of three factors - **(i)** a lack of trust in the technology, **(ii)** the fear of their profession becoming redundant, and **(iii)** the technology interfering with the nicest part of their job - driving.

As for HDP, this negative sentiment stemmed mostly from a lack of trust in the technology. Previous research has reported similar results (Neubauer et al., 2019; Fröhlich et al., 2018). However, studies have shown that drivers become more receptive and accepting once they have experienced driving in a platoon (Castritius et al., 2020b). The positive outlook towards ACC from the drivers in our focus groups suggest that they might also be similarly accepting towards HDP since one can reasonably argue that it is more advanced form of ACC. Furthermore, the fear of being made redundant is not very strong since drivers still need to be active and have a major role to play.

However, the same cannot be said for the more advanced forms of platooning, where all of these factors play a greater role. Drivers found it even harder to trust this more disruptive technology since they would have ceded control. In addition, while HDP might affect a driver's task on certain sections of their route, HDP-IP and HP would potentially change the fundamental nature of a truck driver's job while slowly decreasing their levels of involvement and control. The system takes over a sizeable part of the decision-making process, which generally decreases acceptance (Bekier & Molesworth, 2017). The drivers viewed these more advanced forms as something that interfered with the true essence of being a truck driver. These negative views of drivers toward platooning seem to support (Pink, 2011) who argue that that autonomy is a key driver of intrinsic motivation. Such observations were made even in the context of industrial automation where a reduction in autonomy lead to an increase in stress and alienation (Haddad, 1996; Argote et al., 1983).

Furthermore, this could come with a potential increase in the number of "working" hours (number of hours they need to spend at their job) with inadequate financial compensation.

As the system slowly takes over more tasks, it might dissect a truck drivers job into activities that each carry a different value and require a different skill. A possible consequence is that drivers are employed only for those activities they add value to. The other activities could either be automated or performed by lower wage workers. This could indicate the advent of Taylorism (see Taylor (1911)), which the trucking industry has largely escaped thus far (Aho, 2018).

With this progression, the job description of a truck driver might look different in the future. Such trends are already visible in certain areas - for example, ports and terminals. Gekara & Thanh Nguyen (2018) conclude that automation has created new roles in addition to displacing and transforming the more traditional operations ones, with a greater focus on soft skills and computer proficiency. This calls for a rethinking of training and education (Nedelkoska & Quintini, 2018), something which the drivers indicated as well.

It is impossible to make accurate predictions about the acceptance and use of future technologies based on focus group research alone. Rather, much additional research is necessary especially to study post-experience acceptance. Given the pace of development of technology, it is plausible that the advanced platooning forms become a reality in the not too distant future. One can use the insights from this study to conduct a study similar to that of Castritius et al. (2020b) for the advanced forms.

Castritius et al. (2020b) postulate that drivers with a general positive attitude towards technology would be more willing to use platoon technology. Many of the drivers that drive trucks in platoons may come from the next generation, which is likely to be more positive towards technology (Olson et al., 2011). Furthermore, in this future generation, the decision to join the trucking industry as a 'driver' in a platoon would be based on different expectations, compared to the current generation of drivers who might feel that platooning technology is being forced upon them. However, it is unclear whether their attitude towards platooning will be more positive since the technology takes away what many consider to be the enjoyable parts of the job and reduces autonomy. In any case, drivers would need to undergo adequate training and education before being able to drive platoons. In general, drivers that took part in our focus groups had a limited prior understanding of how platooning works. Therefore, it might be in a company's best interests to inform drivers thoroughly on these developments early in the planning phases. As indicated, drivers thought that platooning will become a reality in any case and involving them in the planning phases would provide relevant input for a smooth implementation of the technology and it could possible lead to higher levels of acceptance by gradually adjusting expectations.

Another perspective that deserves further study, is that of labor relations at an industry level. In the past, rapid automation of industries coincided with particularly heated debates and fraught relations between employers and employees, e.g. triggering the founding of unions in the late nineteenth and early twentieth century. The trucking industry, which is traditionally heavily unionized, could prove a particularly alluring 'battleground' for those with strong views on the automation of tasks customarily performed by humans. As such, a sociological perspective on the broader impacts of platooning on the trucking industry as a whole, is an important avenue for further research into this emerging transport technology.

5.6 Concluding remarks

The advent of self-driving cars is quickly approaching. As a result, there has been a growing body of research that tries to better understand the different elements that are important for the implementation. We contribute to this body of literature by looking at one of the most likely first implementations of automated driving in an open environment - truck platooning. The aim of this study was to explore the range of opinions about platooning among truck drivers - particularly for the more advanced forms of platooning in which drivers may take a break or be removed from following trucks. To this aim, we conducted a series of focus groups in the Netherlands by visiting truck stops across the country. Drivers in general appear to be fairly negative about using platooning technology since they found it intrusive and hard to trust. Furthermore, they felt it would take away their autonomy and leave them open to exploitation. Further research where drivers actually experience the technology, perhaps by means of a simulator or real-life small scale pilots, would provide valuable insights into the subtle and multi-faceted effects that various specifications of truck platooning technologies might have on how truck drivers perceive and value their job and their interaction with this emerging technology.

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5.7 Appendices

5.7.1 Participant details

Name	Age	Goods	Trip type(s)
James		Container	National and international
William	32	Container	International
John		Container	International
Andrew	45	Keeper	International
Adam		Garbage	National and international
George		Container	National and international
Max	53	Container	National
Simon	50	Container	National
Harry	62	Container	National
Yohan	25	Container	National and international
Ashley	53	Container	National
Daan	57	Container	National and international
Jaap	62	Container	National
Jay	45	Container and cars	National
Michael	55	Container	National
Gabriel	31	Container and cooler	National
Rudy	35	Ferry	National
Martin	63	Ferry	National
Robert	32	Liquid waste	National
Jan	39	Ferry	National
Grant	27	Miscellaneous	International
Shawn	54	Produce, paper, parts	International
Roger	57	Pallets	International
Paul		Container	National
Tim	47	Bulk	National and international

Table 5.2: Details of participants (names have been changed for privacy, empty cells indicate that drivers chose to withhold this information)

6 Conclusions and Future Outlook

In this dissertation, we look at what is likely to be the first implementation of automated driving in an open environment - truck platooning. We do so from two perspectives - planning (P) and behaviour (B). First, we consider the following planning related research objectives -

P1. To identify and characterize different planning challenges that occur while creating and organizing truck platoons. This includes challenges that arise with progress in platooning technology where we may see platoons with trucks in which drivers may rest or platoons in which not all trucks may require drivers.

P2. To assist in strategic and operational decision making by building new and efficient quantitative tools to maximize platooning benefits.

The planning perspective is especially relevant in the initial phases of deployment when not many trucks are equipped with platooning technology, which means platoons have to be carefully planned to be able to reap maximum benefits. We first identify open platoon planning related problems and explain possible solution methods. We then consider two of these problems - one strategic and one operational - for further investigation.

Next, we switch to the behavioral perspective and formulate the following objective -

B1. To review the perceived benefits and hurdles of implementing platooning from a truck driver perspective. This again includes advanced forms where we may see platoons in which drivers may rest or platoons in which not all trucks may require drivers.

Here, we study the acceptance of platooning technology by truck drivers. Without their acceptance, the implementation of not only platooning but also automated driving might suffer. In this concluding chapter, we summarize our key findings and outline future research directions.

6.1 Conclusions

In Chapter 2, we tackle research objective P1 and identify open challenges in platoon platooning. We distinguish three platoon planning settings based on the dynamics - (1) scheduled, when all truck information like schedules is known in advance; (2) real-time, when truck information becomes available closely before their departure; (3) opportunistic, when trucks in close proximity of each other dynamically form platoons without any prior planning. Opportunistic platooning is not likely to be successful in areas of low truck density or when the technology is not yet widespread. In such a case, some planning is needed to maximize benefits. Therefore, much of the platooning research focuses on scheduled platooning (Zhang et al., 2017; Sokolov et al., 2017; Larsson et al., 2015; Larson et al., 2013), while relatively fewer studies look at real-time platooning (Van de Hoef, 2018; Adler et al., 2016) and opportunistic platooning (Liang et al., 2013).

Directing our focus toward scheduled platooning, we identify different possible objectives and constraints. Like much of the literature, one would intuitively seek to minimize system-wise fuel costs. This would also indirectly help minimizing emissions. However, for the sake of increasing trust in platooning at the initial stages, it might be wise to maximize the number of trucks in a platoon. Doing so would potentially involve more truck companies and therefore encourage larger participant pools. Typical constraints for such a problem include time windows, platoon size, technical compatibility, and truck sequencing.

We then provide a framework to classify platooning based on the level of human involvement as below -

> **Human driven platooning (HDP).** All drivers in a platoon are required to be attentive at all times. The drivers in the following trucks receives assistance in the operational tasks such as braking and/or steering tasks but is still in control of the tactical driving tasks such as determining when to change lanes, turn or use signals etc. Nearly all platoon planning literature looks at this form of platooning
>
> **Human driven platooning with in-platoon resting (HDP-IP).** Drivers in the following trucks may rest during the platoon as the following trucks can handle all driving tasks. This could mean that the time as part of the platoon does not count as formal driving time for the driver in the following trucks. Albinski et al. (2020) look at this problem.
>
> **Hybrid platooning (HP).** This type of platooning allows the removal of drivers from one or all the following trucks in a platoon. Drivers would still need to be present when a truck is outside of the platoon. Therefore, drivers may need to be shuttled around between meet/split points of platoons to drive individual trucks to/from these points. To our knowledge, this problem has not yet been researched.

We then explain vehicle routing and network design in the context of platooning before concluding the chapter by outlining four broad areas for future research. Since the publishing of this chapter, researchers have looked at problems in all areas - optimization (Albinski et al., 2020; Larsen et al., 2019; Boysen et al., 2018), network design (Scherr et al., 2020, 2019), system sustainability (Axelsson, 2019; Sun & Yin, 2019), and dealing with uncertainty (Calvert et al., 2019; Jo et al., 2019).

In Chapter 3, we deal with operational decision making in platooning as part research objective P2. We investigate the effects of restrictions on platoon planning. We look at two restrictions, namely - the number of trucks in a platoon and the number of platoons each truck may be part of during its journey. First, we define the unrestricted *Platoon Routing Problem with Time Windows* (PRP-TW). Next, we define two restricted problems called the *Platoon Pair Routing Problem with Time Windows* (PPRP-TW) and the *Platoon Pair Routing Problem*, where platoons can have at most two trucks and each truck can be part of at most one platoon in its journey. We show that both the PPRP-TW and the PPRP can be solved in polynomial time. To efficiently solve these restricted settings, we establish an equivalence between the PPRP and the shortest path problem. Furthermore, we analytically solve the PPRP in the Euclidean plane. Both of these approaches form the core of our heuristics to solve the PRP-TW.

From our computational experiments, we see that the restrictions do not have a significant impact on platooning benefits, that is, simple two-truck platoons already capture most of the platooning benefits. These simple two-truck platoons are much easier to plan since they are not subject to the inter-dependencies that larger and unrestricted settings are. Furthermore, they are more robust to changes. When a truck may be part of only a single platoon during its journey, all platoons are independent so any change in the schedule of one truck will affect only the trucks in one platoon. In the unrestricted case, this single schedule change can quickly propagate and affect many trucks in the system.

We also see that our heuristics perform well, which allows us to use it to simulate larger instances with more trucks. We observe that trucks only need a small amount of flexibility in their time schedules to reap the benefits of platooning. That is, they only need to wait for a very short time and/or make small detours to form platoons. As one would expect, this goes down further when there are more trucks with platooning capabilities - with more potential platoon partners to choose from, trucks do not have to deviate much from their original time schedules and routes to achieve platooning benefits.

In Chapter 4, we consider strategic decision making in platooning as part of research objective P2 and look at the effect of platooning on strategic network design. That is, we design a network to maximize platooning benefits given a budget. In such strategic settings, there is uncertainty in demand, i.e, the origin destination information of trucks and the associated temporal information. To capture this uncertainty, we sample scenarios from a probability distribution. We define and formulate the *Platoon Lane Network Design Problem* (PLNDP). Solving PLNDP with a large number of scenarios is likely to lead to better performing solutions but, at the same time, increases computational complexity.

We propose several methods that blend designs created using multiple solutions of PLNDP each using a subset of the sampled scenarios. From our computational experiments, we observe that these blended designs perform as well as designs created using all the sampled scenarios at once. In addition, we study the impact of temporal constraints by neglecting the element of time while designing the network. We see that neglecting time produces high performing designs in a fraction of the time.

In Chapter 5, we switch to a behavioral perspective and focus on research objective B1. We study acceptance of platooning among truck drivers. With platooning being a potentially paradigm-shifting development, it is crucial that driver views be considered. We explore the range of driver opinions on platooning and how they foresee it affecting their jobs. To do so, we conduct focus groups with truck drivers by visiting multiple truck stops across the Netherlands. We structure the focus groups around the three forms of platooning based on human involvement - HDP, HDP-IP, and HP.

Drivers were generally negative towards platooning. They had reservations about trusting platooning technology especially in complex traffic situations with no margins for error. This became more apparent in the discussions on HDP-IP and HP where the system assumes more control over driving decisions. Drivers felt this would interfere and eventually take way the most enjoyable parts of their job - driving. At the same time, this could come with them having to spend more time at work but not being compensated adequately as their bosses might argue that the system does most of their work. Therefore, drivers were worried they might be open to exploitation. This could eventually lead to drivers being employed only for those activities they add value to. The other activities could either be automated or performed by lower wage workers, which points towards a form of Taylorism (see Taylor (1911)).

In general, we observed that the focus group drivers had a limited idea about platooning. Therefore, it might be in a company's best interests to inform drivers thoroughly on these developments early in the planning phases so that their views are taken into account during any implementation process, which could possible lead to higher levels of acceptance by gradually adjusting expectations.

6.2 Future Outlook

This dissertation explored truck platooning and provided valuable insights from the planning and behavioral perspectives. As is typical with academic research, our work points to several new research avenues. One of the goals of Chapter 2 was to identify future research directions for platoon planning. As indicated in Section 6.1, several authors including ourselves have worked on the areas we pointed out. There is, however, still plenty of room for research. We now delve into these and some other directions for future research.

Optimization. Since the general platoon planning problem is difficult to solve, many researchers resort to using heuristics. Many of these are variants of local search on relatively small problems. (Nourmohammadzadeh & Hartmann, 2019, 2016a,b) do explore several meta-heuristics but there are still others open such tabu-search and simulated annealing especially for real-life platoon problems. Furthermore, given the growing body of literature in this area, the introduction of standard benchmark instances would help make comparisons.

The more advanced forms of platooning present interesting opportunities for research. Albinski et al. (2020); Larsen et al. (2019) look at HDP-IP for the European setting, while similar studies for other regions are non-existent. Furthermore, to the best of our knowledge, HP remains untouched when it comes to planning.

Dealing with uncertainty. In practice, there are likely to be many sources of uncertainty. One of them is uncertainty in travel times, which as of now has only been studied in small settings with two trucks by Zhang et al. (2017); van de Hoef et al. (2017). This uncertainty could be caused by the presence of other traffic on the road. Calvert et al. (2019); Jo et al. (2019) study the effects of surrounding traffic on platoons on single highway stretches. At a higher level, such congestion could mean that certain trucks are rerouted even if it means having fewer platoons. This is conceptually related to the area of traffic assignment.

Uncertainty could also stem from when the truck information becomes available in a real-time setting. Existing research on real-time platooning is relatively scarce and we are not aware of any research that looks at stochastic and real-time arrival of trucks.

System sustainability. At the initial stages of deployment of platooning technology, the small number of participants may mean that there are few chances of forming platoons. Therefore, some intervening steps may be required. For instance, it might be worthwhile maximizing the number of companies involved. Apart from this, governments could use incentive schemes such as subsidies or other cost cuts to encourage participation. Determining these kinds of measures is a potential future direction.

We may also encounter participants behaving strategically in a bid to maximize their own savings to the detriment of the system. Sun & Yin (2019) propose mechanisms to discourage such behavior among trucks traveling on a single freeway segment. Extending this to the network level and studying its effects on the routes and plans of platoons is a natural and relevant next step.

Network design. Platooning could influence other strategic network designs apart from the location of dedicated lanes. For instance, facilities might be located differently to allow trucks to meet up more easily. All of these challenges would evolve as platooning technology progress towards HDP-IP and HP.

In addition, platooning could also affect service network design since it provides more incentive for different operators to collaborate. This would especially make sense when HP in place since trucks could use physical locations of other operators as potential platoon/driver switch points.

Technology acceptance. The focus groups indicated that drivers were not very positive towards any of the platooning forms. Castritius et al. (2020b) found that drivers became more positive towards HDP once they had experienced it. Similar research for the HDP-IP and HP is a logical next step. However, this is dependent on these forms becoming a reality.

It could also be interesting to look at labor relations at an industry level. The trucking industry is heavily unionized and therefore could prove to be a platform for those with strong views against automation of tasks customarily performed by humans. As such, a sociological perspective on the broader impacts of platooning on the trucking industry as a whole, is an important avenue for further research.

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About the author

Anirudh Bhoopalam was born in Bangalore, India. After his schooling, he studied Industrial Engineering and Management, where he picked up an interest in transportation. To learn more, he moved to the Netherlands in August 2014 to pursue a masters degree in Transport, Infrastructure, and Logistics at the TU Delft. Two days after graduating, Anirudh joined the department of Technology and Operations Management at the Rotterdam School of Management, Erasmus University, under the supervision of Prof. Rob Zuidwijk and Dr. Niels Agatz.

Anirudh's research interests include the design, analysis, and optimization of transport systems. His work has been published in Transportation Research Part B and has been presented at several international conferences, including the INFORMS Annual Meeting, International Conference of German Operations Research Society, European Conference on Operational Research, and Triennial Symposium on Transportation Analysis. He has also served as an ad-hoc reviewer of various journals, such as Transportation Research Part B, Transportation Research Part E, and the European Journal of Transport and Infrastructure Research.

Portfolio

Publications

Publications in Journals:

Bhoopalam, A. K., Agatz, N., & Zuidwijk, R. (2018). Planning of truck platoons: A literature review and directions for future research. *Transportation Research Part B: Methodological, 107*, 212-228

Working Papers:

Bhoopalam, A. K., Agatz, N., & Savelsbergh, M. (2021). Scenario-based Platoon Lane Network Design *Available at SSRN*: `http://ssrn.com/abstract=3933988`

Bhoopalam, A. K., van den Berg, R., Agatz, N., & Chorus, C. (2021). The long road to automated trucking: Insights from driver focus groups. *Available at SSRN:* `http://dx.doi.org/10.2139/ssrn.3779469`

Bhoopalam, A. K., Agatz, N., & Zuidwijk, R. (2020). Spatial and temporal synchronization of truck platoons. *Available at SSRN:* `http://dx.doi.org/10.2139/ssrn.3741234`

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TRAIL PhD Congress 2017, Utrecht, The Netherlands

Summary

Multiple companies, research institutes, governments are working to help society smoothly transition into an autonomous vehicle future. This is hardly surprising given that autonomous vehicles have several potential benefits. They reduce human error and inconsistencies and could elevate traffic safety levels and improve traffic flow. They may offer an accessible mode of transport to groups such as the physically challenged and the aged, thereby increasing “equality in mobility”. Furthermore, they improve the productivity of commuters by giving them time to carry out additional tasks. Moreover, autonomous vehicles could change society in more fundamental ways. For example, using autonomous vehicles under a sharing model could eliminate the need for car ownership. Such a model would not only reduce the number of cars but also make more public space available in central urban areas since fewer parking spaces would be required.

Before we witness such a society, there are likely to be multiple transitional steps. Freight transport or, more specifically, commercial trucking is often seen as a promising early application area since there already exist autonomous vehicle technology implementations in closed freight settings - such as warehouses and terminals. Within commercial trucking, the idea of platooning is seen as the first step in the roll-out of automated driving technology on public roads. A platoon is a set of virtually connected trucks that drive behind one another at short headways. The following trucks automatically manoeuvre based on the operations of the leading truck. The main benefits of truck platooning stem from the reduced aerodynamic drag, which leads to a lower fuel consumption and less emissions. Other benefits include a lower likelihood of head-tail collisions, better traffic flow amongst others.

When the deployment of platooning technology is not widespread, some form of planning will be required to maximize platooning benefits. In this dissertation, we look at platooning from two perspectives -

Planning. To establish a platoon, the departure times, travel speeds and the routes of the trucks in the platoon must be synchronized. Longer trips may allow the formation of different platoons at different stages of the trip. Multiple decisions need to be made to plan platoons such (1) which trucks platoon together, (2) where and when the trucks join/leave a platoon, (3) the route the platoon will take, and (4) in what sequence the trucks drive within the platoon.

Once the platoons are planned, they will need to be driven by drivers before which they have to accept the changes platooning technology brings to their job. Therefore, we study the acceptance behavior of drivers towards platooning

Behaviour. Platooning technology takes over parts of the driving task meaning drivers no longer exercise the same level of control. Drivers may have problems with losing their autonomy, trusting the technology, and concerns over it interfering with the true essence of their jobs. These could slow down the implementation of platooning and automated driving in general. Therefore, we study factors that influence driver acceptance of platooning.

Chapter 2 classifies the different planning problems that arise in truck platooning and positions these in the transport optimization and operations research literature. We specify possible objectives and constraints for platoon planning and discuss planning dynamics - ranging from scheduled where everything is known and planned in advance; to opportunistic where trucks from platoons with other trucks they encounter on the road. We then classify the platooning literature based on - (1) flexibility in routing and presence of restrictions on platoon size; (2) level of involvement of human drivers in a truck in a platoon. While doing so, we also provide an outlook for studying the settings that have not gotten attention yet. Following this, we discuss how platooning affects traditional vehicle routing and network design settings. Finally, we identify four areas for future research in platooning - (1) optimization and development of heuristics; (2) Dealing with uncertainty; (3) system sustainability to ensure long-term success; and (4) network design.

Chapter 3 builds algorithms to route trucks in platoons with a specific focus on finding fast solution methods for problem settings in which two trucks platoon together and all trucks are in at most one platoon per trip. We define and solve the *Platoon Routing Problem with Time Windows* (PRP-TW), which has no such restrictions. To study the effects of the restrictions, we define special cases - the *Platoon Pair Routing Problem with Time Windows* (PPRP-TW) and the *Platoon Pair Routing Problem* (PPRP). We establish an equivalence of these restricted problems with the shortest path problem. Using this, we build several fast heuristics to solve the PRP-TW. By means of a computational study, we compare how these different models perform on a set of practically relevant instances representing the Netherlands. We observe that the heuristics perform well. Moreover, we see that simple two-truck platoons capture most of the potential savings of platooning.

Chapter 4 looks at strategic network design with truck platooning. Giving platoons dedicated lanes may help avoid dangerous traffic interactions and prolong the life of regular roads by reducing wear and tear caused by trucks. We determine the best parts of a network to add dedicated platooning lanes to so as to minimize emissions given a budget. We define and formulate the *Platoon Lane Network Design Problem* (PLNDP), where we model the uncertainty in truck flows by using scenarios. Given that settings with a large number of scenarios are computationally difficult to solve, we propose methods to blend designs obtained from solving PLNDP multiple times, each with fewer scenarios. From our computational experiments, we observe that combining designs of obtained by solving PLNDP with few scenarios leads to comparable savings as those obtained by with many scenarios, in much quicker time.

Chapter 5 studies truck driver acceptance of platooning technology with a focus on the advanced forms where the system performs most of the driving task. We study the range of driver opinions that exist about platooning technology. Given this exploratory goal, we conduct focus groups with truck drivers at different truck stops in the Netherlands. These focus groups indicate that drivers foresee that platooning will eventually become a reality but believe it will have a negative impact on the quality of their work and their job satisfaction. They see platooning affecting the part of the job they enjoy they most - driving - while reducing their autonomy and freedom. This chapter opens the pathway towards more concerted, quantitative, and confirmatory research efforts in the area.

Samenvatting (Summary in Dutch)

Verschillende bedrijven, onderzoeksinstituten en overheden werken mee om de maatschappelijke overgang naar een toekomst met autonome voertuigen soepel te laten verlopen. Dit is niet zo verrassend aangezien autonome voertuigen een aantal potentiële voordelen bieden. Ze verminderen het aantal menselijke fouten en inconsistenties en kunnen de verkeersveiligheid en verkeersdoorstroming verbeteren. Ze kunnen auto's toegakelijker maken voor mensen met een lichamelijke beperking of ouderen. Dit verhoogt de gelijkheid in mobiliteit. Ook kunnen zede productiviteit van forenzen verbeteren doordat zij hun reistijd kunnen benutten om extra werk te doen. Bovendien zouden autonome voertuigen kunnen zorgen voor fundamentelere veranderingen in de maatschappij. De behoefte aan het hebben van een eigen auto kan worden weggenomen door het gebruik van autonome voertuigen in een deelautomodel bijvoorbeeld. Zon model vermindert niet alleen het aantal auto's, er komt ook meer openbare ruimte vrij in stedelijke gebieden omdat er minder parkeergelegenheid nodig is.

Maar voor onze maatschappij zo ver is, zullen er waarschijnlijk nog verschillende overgangsstappen plaatsvinden. Vrachtvervoer, of beter gezegd commercieel vrachtvervoer over de weg, wordt vaak gezien als een veelbelovend eerste toepassingsgebied omdat de technologie van autonome voertuigen al wordt toegepast in een gesloten omgeving zoals magazijnen en terminals. Binnen het commerciële vrachtvervoer wordt platooning gezien als de eerste stap naar geautomatiseerde rijtechnologie op de openbare weg. Een platoon (peloton) is een reeks virtueel verbonden trucks die op korte afstand achter elkaar rijden. De achterste trucks volgen automatisch de chauffeur van de voorste truck. De belangrijkste voordelen van truck platooning komen voort uit de verminderde luchtweerstand, die zorgt voor minder brandstofverbruik en een lagere uitstoot. Andere voordelen zijn onder andere minder kans op kop-staartbotsingen en betere verkeersdoorstroming.

Wanneer de inzet van platooning-technologie nog niet wijdverbreid is, is er enige vorm van planning nodig om de voordelen van platooning zo groot mogelijk te laten zijn. In dit proefschrift kijken we naar platooning vanuit twee perspectieven:

Planning. Voor het samenstellen van een platoon moeten de vertrektijden, rijsnelheden en routes van de trucks worden gesynchroniseerd. Voor langere ritten kan het mogelijk zijn dat er op verschillende trajecten van de rit verschillende platoons worden geformeerd. Er moeten verschillende beslissingen worden genomen om platoons te plannen, zoals (1) welke trucks er samen in een platoon rijden, (2) waar en wanneer trucks zich bij een platoon voegen of het verlaten, (3) welke route het platoon neemt, en (4) in welke volgorde de trucks rijden binnen het platoon.

Zodra de platoons gepland zijn, zijn er chauffeurs nodig. Maar voor ze hieraan beginnen, moeten de chauffeurs de veranderingen accepteren die de platooning-technologie met zich meebrengt in hun werk. We bestuderen daarom het acceptatiegedrag van chauffeurs ten opzichte van platooning.

Gedrag. De platooning-technologie neemt delen van de rijtaak over en dit betekent dat chauffeurs niet langer dezelfde mate van controle uitoefenen. Chauffeurs kunnen het verliezen van hun autonomie als vervelend ervaren, en kunnen zich zorgen maken over de betrouwbaarheid van deze technologie die zich bemoeit met de essentie van hun werk. Deze weerstand en zorgen kunnen de uitrol van platooning, en geautomatiseerd rijden in het algemeen, vertragen. Om die reden bestuderen we de factoren die chauffeursacceptatie van platooning beïnvloeden.

Hoofdstuk 2 classificeert de verschillende planningsproblemen die bij truck platooning voorkomen en positioneert deze in het kader van de onderzoeksliteratuur over vervoersoptimalisatie en -activiteiten. We specificeren mogelijke doelstellingen en belemmeringen voor platoon-planning en bespreken de planningsdynamiek van een geregelde planning waar alles van tevoren bekend en gepland is, tot een opportunistische planning waar trucks platoons vormen met andere die ze op de weg tegenkomen. Daarna classificeren we de literatuur over platooning op: (1) routeflexibiliteit en aanwezigheid van omvangslimieten voor platoons, en (2) de mate van betrokkenheid van menselijke chauffeurs in een truck binnen een platoon. Zo bieden we ook een raamwerk om de vraagstukken te bestuderen waar nog geen aandacht voor is geweest. Hierna bespreken we hoe platooning de traditionele parameters voor routeplanning en netwerkontwerp beïnvloedt. Ten slotte identificeren we vier gebieden voor toekomstig platooning-onderzoek: (1) optimalisatie en ontwikkeling van heuristieken, (2) omgaan met onzekerheden, (3) bestendigheid van het systeem voor succes op de lange termijn, en (4) netwerkontwerp.

Hoofdstuk 3 gaat over algoritmes om de routeplanning voor trucks in platoons te maken met een specifieke focus op het vinden van snelle oplossingsmethoden binnen situaties waarin twee trucks samen in een platoon rijden en alle trucks aan maximaal één platoon per rit deelnemen. We definiëren het zogenaamde Platoon Routing Problem with Time Windows (PRP-TW), oftewel het platoon-routeplanningsprobleem met tijdvensters, dat dergelijke restricties niet kent, en lossen dit probleem op. Om de effecten van de restricties te bestuderen, definiëren we speciale gevallen voor platoonkoppels: het Platoon Pair Routing Problem with Time Windows (PPRP-TW) en het Platoon Pair Routing Problem (PPRP). We laten zien dat deze versies van het probleem kunnnen worden opgelost door het te formuleren als eenkortstepad-probleem. Door hier gebruik van te maken, creëren we een aantal snelle heuristieken om het PRP-TW probleem op te lossen. Door middel van simulatiestudies vergelijken we hoe deze verschillende modellen presteren in een reeks praktische, relevante op basis van het Nederlandse wegennetwerk. We zien dat de heuristieken goed presteren. Bovendien zien we dat door simpele platoons bestaande uit twee trucks het grootste deel van de mogelijke besparingen door platooning al wordt bereikt.

In hoofdstuk 4 kijken we naar strategisch netwerkontwerp voor truck platooning. Door platoons op speciale rijstroken te laten rijden, kunnen gevaarlijke verkeersinteracties worden vermeden en kan de levensduur van reguliere wegen worden verlengd vanwege minder slijtage veroorzaakt door trucks. We bepalen waar we het best in het netwerk de speciale platooning-rijstroken kunnen aanleggen om de uitstoot te minimaliseren, gegeven een bepaald budget. We definiëren en formuleren het Platoon Lane Network Design Problem (PLNDP), oftewel het stochastische netwerkontwerpprobleem met truck platooning, waarin we de onzekerheid in de vraag modelleren met behulp van scenario's. Gegeven het feit dat omstandigheden met een groot aantal scenario's rekenkundig moeilijk op te lossen zijn, stellen we methoden voor om ontwerpen te combineren die verkregen zijn door het PLNDP meerdere keren op te lossen met minder scenario's. Uit onze rekenkundige experimenten leiden we af dat het combineren van ontwerpen verkregen door het PLNDP op te lossen met weinig scenario's leidt tot vergelijkbare besparingen als ontwerpen verkregen door het PLNDP op te lossen met veel scenario's.

Hoofdstuk 5 bestudeert de acceptatie van platooning-technologie door vrachtwagenchauffeurs gericht op de geavanceerde vormen waarbij het systeem het grootste deel van de rijtaak uitvoert. We bestuderen de meningen van chauffeurs over de platooning-technologie. Omdat hert gaat om verkennend onderzoek organiseren we focusgroepen met vrachtwagenchauffeurs op verschillende truckstopplekken in Nederland. De uitkomst van deze focusgroepen is dat chauffeurs verwachten dat platooning uiteindelijk realiteit zal worden, maar denken dat het een negatieve invloed zal hebben op de kwaliteit van hun werk en op hun werkplezier. Zij zien dat platooning juist dat deel van hun werk zal beïnvloeden waar ze het meest van houden het rijden zelf terwijl het hun autonomie en vrijheid zal beperken. Dit hoofdstuk is een waardevolle eerste stap naar meer onderzoek op dit gebied.

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Many companies, universities, and governments are working to advance automated driving technology and make an "autonomous vehicle society" a reality. As with any such disruptive innovation, there are likely to be transitional steps, with truck platooning often recognized as the first. Using automated driving technology, a set of trucks may be virtually connected and driven at short headways in a platoon. This decreases air-drag and thereby fuel consumption, which in turn reduces emissions. Other benefits of platooning include improved road capacity utilization, higher traffic throughput and a lower risk of head-tail collisions. In this dissertation, we study platooning from two perspectives - planning and behavior.

We review the platoon planning literature and identify various planning challenges that can occur in platooning and link them to the operations research literature. To be part of a platoon, a truck may have to wait at a certain location or make a detour to meet up with other trucks. Therefore, to fully reap the benefits of platooning, one needs to carefully plan and synchronize the departure times, speeds, and routes of the trucks. With many trucks, this becomes complicated especially when trucks can join multiple platoons along their journeys.

Alongside planning aspects, we study how truck drivers perceive platooning technology. With technological progress, the system will take over more and more of drivers' tasks. Implementing platooning without considering driver views could leave them feeling disgruntled, slowing down the adaptation of automated driving in the process. Focus groups indicate that Dutch truck drivers foresee that platooning will eventually become a reality but believe it will have a negative impact on the quality of their work and their job satisfaction.

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