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Designing and Scheduling Cost-Efficient Tours by Using the Concept of Truck Platooning

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Abstract

Truck Platooning is a promising new technology to reduce the fuel consumption by around 15% via the exploitation of a preceding and digitally connected truck's slipstream. However, the cost-efficient coordination of such platoons under consideration of mandatory EU driving time restrictions turns out to be a highly complex task.

For this purpose, we provide a comprehensive literature review and formulate the exact EU-Truck Platooning Problem (EU-TPP) as an Integer Linear Program (ILP) which also features a hypothetical task-relieving effect for following drivers in a convoy. In order to increase the computational efficiency, we introduce an auxiliary constraint and two hierarchical planning-based matheuristic approaches: the Shortest Path Heuristic (SPH) and the Platoon Routing Heuristic (PRH).

Besides a qualitative sensitivity analysis, we perform an extensive numerical study to investigate the impact of different critical influence factors on platooning, being of major political and economic interest.

Our experiments with the EU-TPP suggest remarkable fuel cost savings of up to 10.83% without a 50% task relief, while its inclusion leads to additional personnel cost savings of up to even 31.86% at best with maximally 12 trucks to be coordinated in a recreated part of the European highway network. Moreover, we prove our matheuristics' highly favorable character in terms of solution quality and processing time.

Keywords: autonomous transport; Truck Platooning; driving time and rest periods; cost-efficient routing & scheduling; computational efficiency.

1. Introduction

These days, the entire automotive and transport industry faces radical changes. Next to the consumers' increasing desire for ecologically compliant mobility in a more and more urbanized world, ongoing progresses towards autonomous driving, electric mobility as well as a rapidly growing e-commerce sector necessitate new concepts to make transport more efficient. While the aspect of private transportation gets addressed by approaches like car sharing or multimodal mobility of passengers, designing and scheduling more efficient truck tours represents the key challenge for the logistics business – be it from an environmental perspective or in terms of distance- and time-dependent variable transport cost.

The so-called 'Digital Age' offers new opportunities in this regard. Volkswagen Truck & Bus Group's newly created cloud-based logistics platform RIO is one such emerging business model which particularly addresses the issue of efficient fleet management. Its aim is basically to collaboratively connect the stakeholders of the entire value-added chain with each other in order to meet their respective transport requirements even better (see RIO, 2017). LOADFOX, for example – a sub-platform for freight ridesharing – allows schedulers to increase their trucks' capacity utilization, resulting in more profitable journeys (see LOADFOX, 2017). However, there is another promising technology called 'Truck Platooning' which is getting closer to becoming a reality soon. It has the potential to bring transportation efficiency to a whole new level.

1.1. Background and motivation

"Truck Platooning is the future of transportation in which trucks drive cooperatively at less than 1 second apart made possible by automated driving technology" (Janssen et al., 2015). The basic idea behind platooning is as simple as effective: two or more trucks form a digitally connected convoy with small inter-vehicle distances such that especially the non-leading vehicles can benefit from a reduced aerodynamic drag when trailing – and thus primarily reduce their

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fuel consumption. Being equipped with sensor technologies like Lidar (Light detection and ranging) and Radar (Radio detection and ranging), distance and speed measurements allow the vehicles to communicate with each other (Vehicle-to-Vehicle or V2V). Additionally, geographical information provided via GPS (Global Positioning System) and instructions given by roadside controllers (Vehicle-to-Infrastructure or V2I) enable the proper formation, navigation and dissolution of platoons. While the leading truck is driven manually, the trailing vehicles are controlled automatically by an on-board system called Cooperative Adaptive Cruise Control (CACC). In other words: if the Platoon Leader (PL) brakes, decelerates or accelerates, the Platoon Followers (PFs) brake, decelerate or accelerate with a negligible time lag as well (see Alam, 2014). Not least because of this synchronized digital process sequence, semi-autonomous "[t]ruck platooning can be considered as a first step towards automated freight transportation" (Bhoopalam et al., 2018). Figure 1 illustrates the fundamentals of platooning by means of three wirelessly connected Heavy-Duty Vehicles (HDVs) on a highway network.

This promising transport concept leads to a whole range of significant advantages.

First and foremost, such a road train configuration results in an increased overall fuel economy of trucks – especially for those exploiting the slipstream effect behind the PL. Different studies and experiments have been carried out to investigate the fuel consumption behavior of single HDVs within a platoon in different scenarios (see Al Alam et al., 2010; Alam, 2014; Alam et al., 2015; Bonnet and Fritz, 2000; Davila et al., 2013; Lammert et al., 2014; Tsugawa, 2013). Their results show saving potentials of up to 22% for the PF under idealized highway conditions, while even the leading vehicle can profit from a reduced air pressure and less turbulences behind the vehicle with a fuel saving rate of up to 10%. However, there are many factors which have an influence on the respective fuel reduction potential. Next to the number of vehicles in a platoon, its vehicles' masses (incl. freight) and types (i.e. dimensions, engine power, fuel consumption etc.), the trucks' individual positions within the convoy as well as the leader's driving behavior, external aspects such as traffic, road conditions, weather and varying road topography also play an important role. The platoon's travelling speed and the chosen inter-vehicle gaps determine the fuel reduction factor most significantly though – reducing the aerodynamic drag by up to 40%. Consequently, fuel saving potentials between 5% - 15% for the PF seem realistic on highways according to current research while those for the PL usually result much lower in most of the cases (see Eckhardt, 2015; Larson et al., 2013).

But platooning is not only supposed to enhance fuel economy. Next to an increased utilization of the trucks due to less idle times, it is expected that this technology will have a considerable influence on labor costs as well. Janssen et al. (2015) give an outlook and highlight two main reasons. On the one hand, the following driver's efficiency can be optimized by performing administrative tasks while trailing semi-autonomously behind a preceding truck. On the other hand, this reduced required alertness could be seen as a break or rest period, at least to some extent. Such considerations would allow driving times to be extended without the urgent need to take mandatorily prescribed pauses. Less crowded parking spaces would be a positive side effect here. As a consequence, legal changes to Regulation (EC) No 561/2006 on driving times, breaks and rest periods as well as to Directive 2002/15/EC on truckers' working times in the European Union (EU), among other things, could become indispensable. In the end, less time spent next to the road leads to a higher overall cost efficiency level of an individual truck. So the impact of platooning on EU-law will become a critical aspect.

Along with advantages for the transport industry's business case comes also a noteworthy societal benefit. Less congested highways with more space for other road users will improve the traffic flow. Semi-autonomous platoons will enable safer roads by minimizing accidents or damages caused by human error. And finally, such convoys will also have their contribution to a cleaner transportation environment by reducing CO2 emissions through an increased fuel efficiency.

Figure 2 summarizes the main advantages provided by the concept of platooning.

According to Wittenbrink (2011, pp. 1-46), the two major cost drivers in trucking are fuel and personnel cost – making up about one third of the overall long-haul Total Cost of Ownership (TCO) each. Hence, platooning represents a highly attractive approach to make transportation tasks more efficient by exploiting its fuel as well as its labor cost saving potentials when designing and scheduling tours.

The topicality and enormous economic interest in this field of research is justified by its relative feasibility compared to full autonomous driving. The Bavarian truck manufacturer MAN Truck & Bus and the logistics specialist DB Schenker have already started a cooperation to be the first companies testing the concept of platooning in their everyday operations from early 2018 on. Strongly supported by the German Federal Ministry of Transport, the highway A9 between Munich and Nuremberg will serve as a test field for this purpose (see Transport-Online, 2017). Moreover, the European Commission is well aware of this technology's value for Europe's competitiveness and therefore promoted the EU Truck Platooning Challenge 2016 – an initiative to get first practical insights into the implications of platooning, where truck manufacturers all across Europe have been invited to participate. Thus, from a technical point of view, platooning is already at an advanced stage and all stakeholders put strong efforts into its final realization (see Eckhardt, 2015; Eckhardt, 2016). Nevertheless, the implementation of such a new concept into real-world applications bears many new challenges for an efficient truck tour management approach – some of which we want to address within the framework of this thesis.

1.2. Problem formulation and major research objectives

The first and most essential part in designing cost-efficient tours by making use of digitally connected road

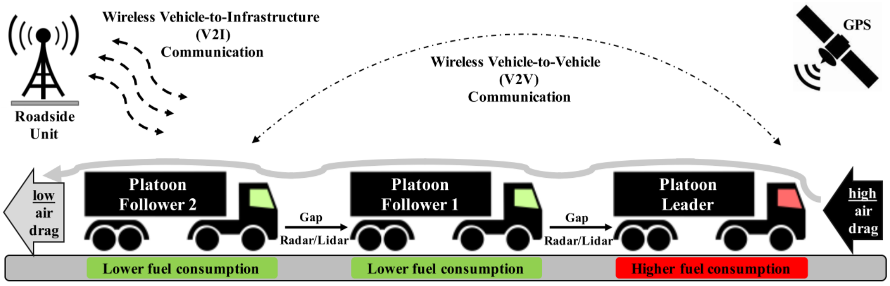

Figure 1: Basic mechanisms behind the concept of truck platooning (based on Alam, 2014 and Janssen et al., 2015)

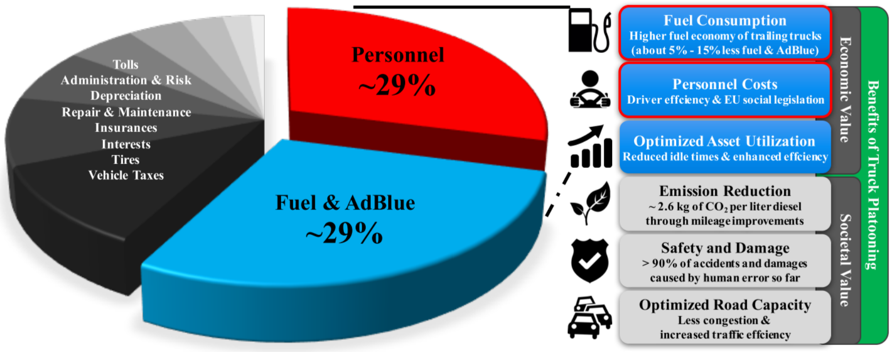

Figure 2: Major benefits of truck platooning (based on Eckhardt, 2015, Janssen et al., 2015 and Wittenbrink, 2011, p. 33)

trains is to enable the formation of such convoys at all. At first glance, this seems straightforward in case two or more trucks start from and drive to the same location. But as soon as slightly divergent time windows come into play and / or different locations need to be approached, generating fuel savings gets more difficult. The upcoming challenge in the future, however, lies in the coordination of trucks from various shipping companies to form platoons as each transport order has its own local and temporal restrictions. Additional complexity is included when these convoys form, dissolve and merge again – with different trucks from different origins to different destinations and, of course, with their respective time windows that must be met.

Another very important aspect which fleet managers have to take into account in their tour planning is the EU social legislation on mandatory driving times, breaks, rest periods and working hours. Being a complex task in itself, scheduling the required periods of standstill at the right time and at the right place becomes even more critical when involving the concept of truck platooning in the decision-making process. Unfavorably scheduled pauses could potentially lead to missed platooning opportunities. In the end, such breaks and rests limit the truck drivers' required flexibility to a certain extent. Although "[t]his can affect the possibilities for platoon formation as well as fuel-saving potentials" (Liang et al., 2016a) negatively, the actual chances provided by platooning itself could have a positive effect on driving times in turn. As already indicated above, the PF could even get a driving time 'discount', also referred to as 'task relief', if the necessary legal changes are addressed by the EU – an aspect which could make platooning even more attractive than anyway with the expected fuel savings (see Bhoopalam et al., 2018; Tavasszy, 2016; Van De Hoef et al., 2015a). The reduced required attention when trailing in the slipstream might have a considerable impact on the amount of mandatory pauses that need to be considered, finally leading to reduced personnel cost for the logistics companies.

In certain cases, carriers even deploy two truck drivers to avoid such breaks or rest periods. Thus, manning and platooning are supposed to mutually affect each other as well. Moreover, mandatory idle times at certain locations like specific rest areas or customer sites might also represent real chances to wait for each other during a trip in order to be able to form platoons at all – actually taking best advantage of this originally impeding legal obligation. Otherwise, it would possibly be necessary to schedule some additional waiting times in the road network to merge with other trucks.

To the best of our knowledge, no attempts have been made so far to include the option to platoon when planning a tour under consideration of strict EU driving time regulations – additionally deciding upon single- or double manning. So, be it from a routing or scheduling perspective, platooning brings up a whole new set of challenges which need to be addressed for the efficient coordination of trucks.

At the end of the day, the whole concept of driving in a road train with small inter-vehicle distances to save fuel only works if drivers have an incentive to lead such a convoy of HDVs. Since the PFs will usually be the profiteers of trailing in the slipstream, Liang et al. (2016b) and Zhang et al. (2017) point out that the benefits of platooning must be shared fairly to meet the carriers' mutual interests. We are not aware of any study which – at least and at first theoretically – paid attention to potential compensation mechanisms between PLs and PFs up until now.

Consequently, it is absolutely necessary to shed more light on designing and scheduling cost-efficient tours by using the concept of truck platooning, considering the aforementioned aspects in more detail. For this purpose, our motivation is to address the subsequent six research questions:

(i) How can the combinatorial problem of truck routing and driver scheduling be efficiently extended with platooning decisions under mandatory service time regulations in the EU?

(ii) Which financial and computational effects can be expected from the coordination of truck platoons by means of such an integrated framework?

(iii) What is the impact of coordinating an increasing amount of trucks – be it from a single origin or from dispersed locations in the road network?

(iv) To what extent do compulsory breaks, daily rest periods, restricted time windows, manning options, different wage levels and aspects relating to fuel consumption affect the coordination of truck platoons?

(v) Which implications can be derived from platooning-driven legal amendments of European social transport law if politics decides upon a specifically defined task-relieving share for less strained followers in a platoon?

(vi) How can the generated cost savings be shared fairly among the respective collaborating partners within a platoon?

Therefore, the major research goals of our work include the following:

1. Elaboration of the current state of literature and research relating to the coordination of platoons as well as to mandatory service time restrictions in the EU.
2. Formulation of a suitable optimization problem for road transportation in the EU which involves the promising concept of truck platooning.
3. Development of computationally efficient heuristic solution approaches.
4. Investigation of the financial benefits provided by EU-constrained platooning – both from a fuel and personnel cost perspective.
5. Evaluation of the consequences which could arise from potential legal adaptations in the EU with regard to a task-relieving effect from trailing in the slipstream of a preceding truck.
6. Analysis of different influence factors on the coordination of platoons (e.g. the chosen coordination approach with regard to local / temporal start conditions of affected trucks, manning options, varied shares of a task relief, fuel consumption behavior, hourly wages, lateness penalties etc.).
7. Identification and qualitative discussion of appropriate benefit / cost sharing mechanisms for platooning purposes.
8. Provision of further directions for future platooning-related research.

Our primary goal is to provide a sound theoretical and experimental foundation to contribute to bringing the concept of truck platooning one step closer to implementation in the everyday transport business. As mandatory EU driving time legislation represents a crucial part in designing and scheduling cost-efficient tours, we see a strong need to investigate its interaction with the various facets of platooning. Here, in turn, adequate financial incentives must be in place and need to be studied to make it happen at all.

1.3. Thesis outline

In order to be able to make valid statements about the above elaborated research questions, this thesis is structured as follows:

Chapter 2 presents the basic legal framework regarding mandatory service time regulations for truck drivers in the EU and gives a first glimpse into its interaction with platooning. Next, chapter 3 provides a comprehensive review of existing literature and research contributions about studied approaches to form, navigate and dissolve platoons for road transport purposes as yet. Herein, the inclusion of compulsory EU driving and working time restrictions into routing and scheduling problems is considered as well. After summarizing and discussing the current state of literature for our specific purposes, we formulate the complex EU-Truck Platooning Problem (EU-TPP) as an Integer Linear Program (ILP) in chapter 4 to provide the basis for optimal platooning decisions in a European framework. The issue of its computational efficiency is addressed by smart implementation and two related matheuristic approaches based on the principles of hierarchical planning: the Shortest Path Heuristic (SPH) and the Platoon Routing Heuristic (PRH). Subsequently, chapter 5 presents the underlying experimental setup for our investigations along with a validation of our approaches. Key performance indicators are defined, before we finally conduct an extensive computational study in chapter 6 to specifically achieve our major research objectives (4) to (6). The accompanying, well-founded discussion dedicates itself to our experimental outcomes in order to be able to provide valid recommendations and answers for the upcoming political and economic challenges in the field of truck platooning. Afterwards, we additionally outline first theoretical insights on platooning-based mutual compensation mechanisms in chapter 7 to emphasize their importance for the successes of platooning. Chapter 8 rounds off the thesis with a conclusion about our research results and gives a broad outlook on future work.[1]

2. Truck driver scheduling in the EU – legal framework and future prospects

Before actually presenting the current state of literature and research of truck platooning-based fleet management approaches, we first need to depict the essentials of mandatory service time regulations in the EU in order to be able to formulate an appropriate optimization problem later on. After this, we give a first glimpse of a quite possible legal adaptation scenario relating to a task-relieving effect for PFs and its consequences for the daily transport business when the concept of platooning comes into play.

2.1. Mandatory service time regulations

There are basically two major sets of rules which are primarily stipulated by the European Parliament and the European Council for reasons of road safety due to fatigue, health and fair competition. On the one hand, truck drivers have to abide by Regulation (EC) No 561/2006 (see European Union, 2006) which regulates maximum driving times, minimum breaks and rest periods for different time horizons. Directive 2002/15/EC (see European Union, 2002), on the other hand, extends this temporal framework to working conditions in general, involving both times on and off the vehicle while being on duty. Since we will put our emphasis on the former one throughout this thesis, the latter will only be outlined briefly to stimulate future elaborations, e.g. in the field of different multi-stop Vehicle Routing Problems with Time Windows (VRPTW).

Planning based on Regulation (EC) No 561/2006 exhibits a high complexity which becomes best apparent when looking at the numerous possible rules and their modifications which apply to different intertwined time horizons. Figure 3 schematically depicts their basic relationship to each other.

After a maximum driving time of 4.5 h, a minimum break of at least 45 min needs to be taken if no daily rest period is required. This automatically becomes necessary when a maximum daily driving time of 9 h is reached, leading to a minimum mandatory rest period of 11 h. A new daily rest is indispensable within every 24 h period after the end of a previously taken daily or weekly rest. In general, weeks must be separated by such a minimum weekly rest period of 45 h. Moreover, the accumulated driving time within two consecutive weeks may not exceed the limit of 90 h, whereas one week may not exhibit more than 56 h of driving on balance between Monday 0:00 and Sunday 24:00 o'clock.

However, there are also some modifications to these basic rules which can enhance the fleet operators' flexibility. Making use of the splitting principle, the 45 min break can be divided into a 15 min and a 30 min part at minimum by also following this exact order. Furthermore, it is allowed to split the 11 h daily rest into two consecutive minimum rest periods of 3 h and 9 h respectively in the same way – leading to one extra hour in exchange for more flexibility though. Additionally, there are also several conditional possibilities to resort to extended driving times and reduced rest periods. To mention just a few of such examples: at most twice per week, the maximum daily driving time can be increased from 9 h to 10 h, whereas a reduced weekly rest period of 9 h instead of 11 h may be taken at most thrice per week. But while the aforementioned splitting rules can generally be applied on a regular basis, extended driving times or reduced rest periods taken at one point in time must always be considered explicitly or compensated somehow within a predefined time frame. This turns rule-consistent truck driver scheduling into an even more complex task. Nonetheless, many fleet operators are apt to exploit all these options not primarily for flexibility, but rather for reasons of economic pressure (see Goel and Vidal, 2013).

These above described rules apply to the case of single manning. Deploying two truck drivers (i.e. double manning) entails some easing, also resulting in less interrupted tours. Despite increased personnel cost, this can turn out to be highly favorable, especially in the presence of narrow time windows. Instead of 11 h, a driver in a double-manned truck is bound to take a minimum daily rest period of only 9 h and just within every 30 h period after having finished the last daily or weekly rest period (compared to 24 h in case of single manning). In the end, saving breaks by handing over the steering wheel every 4.5 h represents the biggest advantage of such a configuration – especially in the presence of extremely narrow time windows.

As far as the legal situation in terms of working time is concerned, Directive 2002/15/EC extends some of the above described temporal frames in order to additionally account for work other than driving. Such work can be in the form of (un)loading, truck maintenance, cleaning, transport-related paperwork or waiting times at customer locations. Breaks, rest periods and other freely available times are thus not considered as work. Between 6 h and 9 h of accumulated working, for example, a break of at least 30 min is required – rising up to minimally 45 min when working even longer. As can be seen, this is well in line with Regulation (EC) No 561/2006. By contrast, one special rule still refers to work at night, prohibiting to work longer than an accumulated period of 10 h within a 24 h horizon.

The interested reader may be referred to the respective legal texts for further specific examples, details and explanations.

As the personnel cost are affected significantly by such EU laws, one might take 'accidental' financial reliefs within this big cost category into consideration. However, infringing upon some of these rules can be fined heavily. To this end,

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[1] Please note: Appendix A provides a guiding overview of all the files that have been generated and used throughout our investigations, along with explanations.

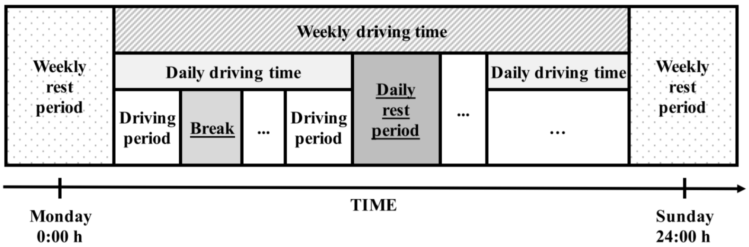

Figure 3: Basic structure of Regulation (EC) No 561/2006 (based on Meyer and Kopfer, 2008)

Regulation (EU) No 165/2014 (see European Union, 2014) on recording equipment in road transport specifies their enforcement by monitoring tachographs. Therefore, we necessarily need to make sure that our later platooning approach models the basic restrictions correctly and in a reliable manner for the respectively chosen time frame.

2.2. Effects of anticipated legal adaptations due to platooning

The EU social legislation on road transport has an enormous impact on the truck drivers' flexibility when it comes to planning their respective tours. And the consideration of platooning will not make this task easier. However, this emerging technology also bears some chances for truck drivers with regard to actually feasible travel ranges without the need to take a compulsory idle time – potentially leading to a more favorable personnel cost structure in the end.

So far, no concrete decisions about an amendment of mandatory driving time regulations under platooning conditions have been made by the EU. Based on a potential task relief when trailing in the slipstream of a preceding truck with less required driver attention, there is only one working paper pointing out a conceivable future interdependence with truck platooning. "Assuming (and this is critical for this value case) that [...] the work time of the second driver would only count for 50% and the two would change leading positions after 3 hours, they could increase their daily travel range each to 960 km" (Tavasszy, 2016) when travelling in tandem at an average speed of 80 km/h. Figure 4 illustrates the maximum possible distance gains when exploiting such considerations compared to the conventional driver scheduling approaches under single and double manning. Since it is our aspiration to cover the whole range of common practice in transport logistics, we also added the latter case by transferring the theoretical thoughts of Tavasszy (2016) from a single truck driver scenario to a setting with two drivers.

As can be seen, relieving adaptations to European transport law in the presence of enough platooning opportunities might have a significant economic impact due to the possibility to delay or even avoid single breaks or daily rest periods by longer granted travel ranges for PFs. In case of double manning, clever switching of platoon roles and truck drivers could potentially lead to a daily trip length of up to even 1920 km without any compulsory breaks because the co-driver in a truck is allowed to take his break time on the vehicle. In other words: the sometimes anyway attractive option to deploy two drivers might even gain in attractiveness. However, the possibility to exploit the slipstream of a preceding truck might suddenly also lead to a single manning decision in cases where double manning would have been the financially advisable alternative before. This becomes best apparent when looking at the extension from 720 km to 960 km for single manning which allows to reach a destination within this range with only one driver now before a daily rest period is actually required.

Although these scenarios seem rather idealistic, they highlight the elementary effects which truck platooning might actually have on driver scheduling and the associated personnel cost efficiency. Therefore, we also intend to take the option of a task relief from trailing into account within our optimal modeling approach.

3. Review of Literature and Research

In this chapter, we provide a comprehensive overview of the actually conceivable coordination principles behind truck platooning and discuss the already existing research contributions in this field. Moreover, further insights into truck driver scheduling literature are given to address the issue of appropriately considering mandatory EU driving time restrictions for our purposes. A review summary where we outline some useful characteristics for our modeling approach rounds off this chapter.

3.1. Coordination approaches for truck platooning

Driven by the objectives of this thesis, it is first of all necessary to understand which concepts of coordinating truck convoys exist at all and are discussed by experts for a close future implementation. Therefore, we describe the generally possible framework of principles for platoons to be formed and dissolved, before having a closer look at the current state of platoon coordination literature in the subsequent sections.

3.1.1. Platoon coordination levels

It is undisputed that there will not be a simple shift from a non-platooning transport sector to a platooning one from one day to the next. Both Bernhart (2016) and Janssen et al. (2015) coincide in revealing that the development path of truck platooning in terms of conceivable coordination levels will contain three major stages on its way to a reliable and

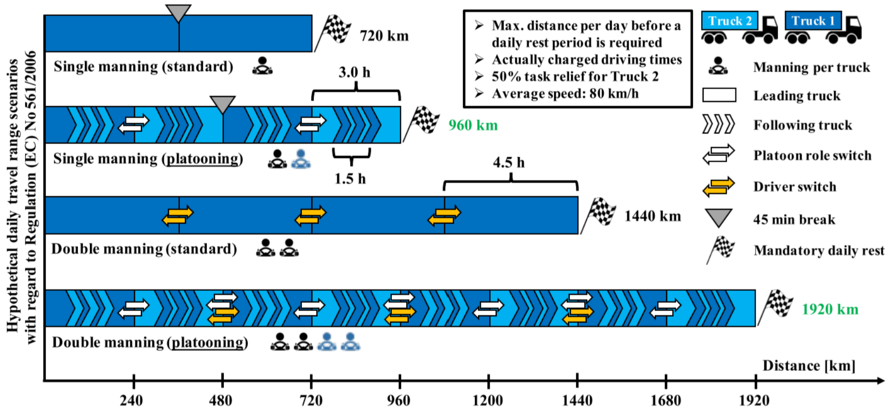

Figure 4: Hypothetical implications of a 50% task relief from trailing (based on Tavasszy, 2016)

widely used transportation concept. These are not strictly separated from each other, but bear an increasing level of planning complexity. Figure 5 illustrates this staged framework.

The first stage will be characterized by "a limited number of vehicles [which] will have been equipped with platooning technology and devices, and widespread market penetration will still be limited" (Eckhardt, 2015). During this initial phase, fleet operators need to plan their trips in advance based on their own vehicles' and drivers' schedules as well as on those of other carriers. A common virtual platform or software where single tours are announced and freely accessible could help in this regard. Provided trip information must at least include a truck's origin and destination locations as well as its earliest possible departure time from and latest possible arrival time at the respective location. But also the specific truck's characteristics, its load or preference for being the PF or PL could be of interest. The single trip schedules would then be matched with each other, resulting in a platoon schedule. Herein, information about who platoons with whom, on which route as well as when and where the vehicles meet for merging is specified (see Bhoopalam et al., 2018). Considering this, Self-Organized Scheduling (SOS) will be crucial for the first successes of platooning in real-world applications. We denominate the mere inclusion of own trucks at this stage as step 1, whereas the extension to inter-fleet planning is denoted by step 2. This additional differentiation is justified by the relative simplicity when starting from the same location at the same time compared to identifying opportunities to meet with other carriers' trucks first in order to be able to platoon at all.

In the next stage, On-The-Fly-Platooning (OTFP) will be possible, i.e. forming convoys spontaneously or ad hoc while being on the road. Although an en route intervention with regard to detours, route and schedule adjustments seems feasible to this effect, its realization primarily focuses on the adaptation of speed profiles (see Liang et al., 2014). For this dynamic approach to become a reality in any sense at all, a certain saturation level of respectively equipped trucks on the road must be reached on the transportation market first. Eckhardt (2016) does not expect OTFP to emerge during the next couple of years. However, "economic and societal benefits can be quite significant, as the number of kilometers platooned can increase dramatically" (Janssen et al., 2015), especially on corridors with a high truck density. As one can imagine, these benefits could even increase when additional planning steps before and during the trip are included.

This aspect leads us directly to the last stage, namely Orchestrated Platooning (ORP). It basically represents an advanced combination of SOS and OTFP, in which a specialized and independent Platooning Service Provider (PSP) will have a key role. The PSP is thus able to execute both on-road and off-road coordination tasks – be it separately or jointly. Next to reconciling the diverse transport plans from multiple carriers before the trip or even in real time, it is meant to act as an intermediary quality gate according to Janssen et al. (2015). The PSP could check a truck driver's compliance with EU driving time regulations before platooning spontaneously, for example. Thereby, trust between carriers – and more importantly, in the platooning concept itself – is built up and can thus strengthen the potentials of this technology even more.

3.1.2. Platoon formation strategies

After all, these three major stages demand different formation and dissolution strategies. While adjusting "speed is the only option to change in order to form platoons on the fly" (Liang et al., 2014), SOS and ORP do not necessarily have to merely rely on catching up or slowing down. So if a certain degree of centralized planning is involved in advance, scheduling departure times from and arrival times at different locations accordingly along with adapted routing decisions will support the formation of platoons as well. This would also allow trucks to wait for each other at predetermined positions throughout a trip. In particular, taking mandatory breaks or rest periods stipulated by EU law could suddenly turn out to be favorable for the formation of platoons – despite their generally restricting character for truck convoys to emerge. Moreover, accelerating or decelerating and accelerating again during an ad hoc platoon formation phase also causes a decreased fuel economy. This rising fuel

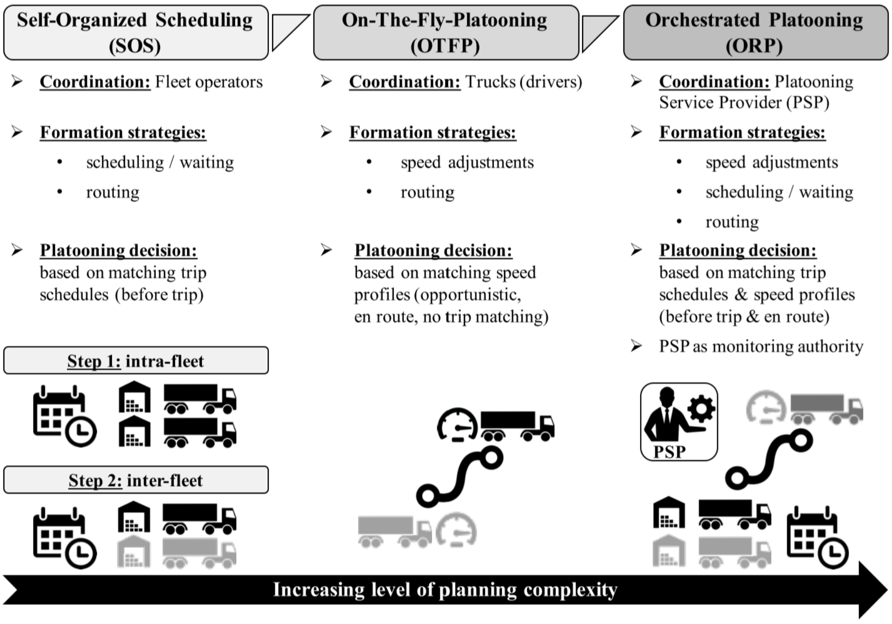

Figure 5: Coordination approaches for truck platooning (based on Bernhart, 2016, Eckhardt, 2015 and Janssen et al., 2015)

consumption would first have to be compensated when platooning on a long enough route segment (see Liang et al., 2016a). Thus, the idea of using meeting points to join each other, as also proposed by Stiglic et al. (2015) for a ridesharing environment, could heavily contribute to the success of platooning. In their study, a significant increase in the number of matched riders and drivers is observable through the introduction of such rendezvous points if riders exhibited a certain willingness to walk. Transferred to the case of truck platooning, either a respective willingness to wait for each other or an anyway compulsory break or rest period would be required instead. Matching seems to be a difficult undertaking in view of strict time windows and other constraints, though. Figure 5 also shows the basic formation strategies in relation to the likely development path of platooning with its respective coordination levels.

Finding and modeling fuel-efficient, (near-)optimal ways for trucks to platoon has attracted researchers more and more during the last years, as can be seen at the years of publication in tables 1 and 2. The different ways to handle this nontrivial task are described and discussed below in order to lay the foundation for our later platooning approach based on mandatory EU driving time restrictions.

3.2. On-the-fly platoon formation based on speed adjustments

The adjustment of speed profiles en route has been identified as one of the major enablers for the formation and dissolution of platoons. Table 1 gives an overview of the most relevant publications in this area of platoon coordination literature.

3.2.1. Speed-up maneuvers

Some of the research contributions in table 1 are specifically focusing on catch up maneuvers of the PF to form a platoon with a potential PL ahead. Larson et al. (2013) formulate the so-called Local Controller Problem in order to maximize the benefits provided by platooning through speeding up. For this purpose, they introduce local route and platooning coordinators at intersections which are meant to decide upon forming a convoy based on a truck's current location, velocity and target destination. According to them, “a global controller attempting to coordinate the routes of every HDV in a real-world scenario is beyond current capabilities” (Larson et al., 2013). As long as the costs for catching up are not higher than the expected fuel savings by trailing, convoys are built. Providing both an exact algorithm for small instances and a fast real time application heuristic based on pairwise comparisons, their formation strategy leads to increasing savings when slight temporal deviations from the vehicles' shortest paths are allowed. An increasing saturation level of the road network shows a positive impact for the effects of platooning as well. The case of every truck solely taking its shortest path from start to end serves as a benchmark for evaluating savings generated by platooning. Larson et al. (2015) substantiate the exact same problem and outcomes with real-world data from HDVs. They illustrate the existence of many chances to platoon in Europe even today and thus argue for the feasibility of their distributed local controller approach.

More generally, Besselink et al. (2016) investigate the chances that modern information and communication technology offers for road freight transportation. In addition, they follow a cooperative look-ahead control strategy to form platoons based on V2V connections and exploiting road grade

Table 1: Overview of platoon coordination literature – part 1

Publication	Platooning decision	Formation strategy	Major research contributions
Besselink et al. (2016)	en route	speeding up (PF)	– cooperative look-ahead control strategy based on optimized velocity profiles – simulations exhibit large fuel savings (consideration of road grade information)
Deng and Ma (2014)	en route	speeding up (PF), slowing down (PL), hybrid	– intelligent, optimal speed planning algorithm based on available real time traffic information while already being in a platoon – higher computational efficiency compared to benchmark dynamic programming approach proven by simulations
Larson et al. (2013)	en route	speeding up (PF), routing	– algorithms based on local controllers in the road network – large savings by slightly speeding up on shortest paths proven by simulations – higher savings with increasing acceptance for longer travel times and with increasing network saturation
Larson et al. (2015)	en route	speeding up (PF), routing	– see Larson et al. (2013) + large scale simulations – substantiation by real-world HDV data to prove feasibility of distributed local controller approach
Liang et al. (2013)	en route	speeding up (PF)	– analytical study based on simulations – introduction of a platooning incentive factor to enable favorable catch up decisions – relatively accurate speeds required to avoid any false positive recommendations
Liang et al. (2014)	before trip, en route	speeding up (PF), scheduling	– map-matching and path-inference algorithms based on real-world application data – significant increase in fuel savings when departure time coordiantion adds to ad-hoc platooning – higher flexibility in departure / arrival time yields even more savings
Liang et al. (2016a)	en route	speeding up (PF), slowing down (PL), hybrid	– algorithm based on pairwise coordination of neighboring vehicles in simulations – speed adjustments of both the PF and the PL result in larger fuel savings than mere catch up maneuvers – negligible effect of road topography on platooning decisions when rerouting is unconsidered
Liang et al. (2016b)	en route	speeding up (PF)	– investigation of control challenges regarding platooning based on simulations – large influence of traffic on platoon merging maneuver – increased traffic density correlated with a later merging point
Saeednia and Menendez (2016)	en route	speeding up (PF), slowing down (PL), hybrid	– optimization problem to investigate a hybrid strategy in contrast to mere catch up / slow down formation strategies – hybrid platooning strategy as fastest and most successful way to form platoons compared to single catch up or slow down strategies
Van De Hoef et al. (2015a)	en route	speeding up (PF), slowing down (PL), hybrid, routing	– introduction of a routing framework for fuel-optimal speed planning based on shortest paths and possible platoon configurations – approximation algorithm as solution approach for formulated optimization problem – influence of velocity on fuel consumption is taken into account explicitly
Van De Hoef et al. (2015b)	en route	speeding up (PF), slowing down (PL), hybrid	– approximation algorithm based on clustering fuel-optimal speed profiles pairwisely – significant fuel savings possible according to simulations
van de Hoef et al. (2016)	en route	speeding up (PF), slowing down (PL), hybrid, routing	– reduction of computational complexity in case of central control through an intelligent algorithm – pairs of trucks which cannot platoon anyway for temporal and geographic reasons are disregarded
van de Hoef et al. (2017)	en route	speeding up (PF), slowing down (PL), hybrid	– formulation of a stochastic dynamic programming problem – maximization of meeting probability at an intersection – applicable to realistic problem instances where travel times are influenced by different factors of uncertainty (e.g. weather, traffic)

data for mere speed-up maneuvers. Considerable savings are achieved by well optimizing the vehicles' speed profiles, especially over hilly segments of the simulation network. Yet, Liang et al. (2016a) conclude that the impacts of road topography on OTFP coordination on a common route segment without the consideration of rerouting turn out to be insignificant.

Despite the demonstrated fuel savings generated by OTFP approaches with mere speed corrections in the aforementioned and subsequent studies and papers, Liang et al. (2014) show that including an additional planning portion in terms of scheduling in the task of platoon coordination can increase platooning benefits notably. According to their investigations, only slight departure time adjustments are sufficient to enhance fuel savings compared to relying on catch up maneuvers only. Based on a map-matching algorithm and therefrom inferred paths in a real-world application setting, they show that yielding more flexibility in the tour schedule has the potential to increase savings even further.

Liang et al. (2013) analytically investigate the implications of catch up maneuvers to form platoons by assuming negligible fuel increases during the acceleration phase. Therefore, they introduce a platooning incentive factor along with a little overhead on top which allows to avoid unprofitable catch up decisions. Since speed usually falls victim to uncertainties, its estimates must be carefully chosen. Moreover, simulations also show that surrounding traffic conditions can heavily affect a truck's ability to merge with others. This can lead to a delayed platoon formation in case of high-density traffic – negatively influencing the resultant benefits of platooning (see Liang et al., 2016b).

3.2.2. Combined acceleration and deceleration approaches

In consequence and presence of such travel time uncertainties, van de Hoef et al. (2017) deal with the dynamic formation of platoons through slight speed adaptations en route, i.e. merging by means of accelerating or decelerating the truck. To this end, they apply an optimal stochastic programming approach which maximizes the probability of two trucks meeting each other at an intersection for platooning purposes. Their technique is demonstrated to be well applicable to real-world merging maneuvers.

Being aware that velocity adaptations have to be justified by long enough joint platooning distances, Liang et al. (2016a) extend their previous simulation results in Liang et al. (2013) by also taking a PL's possible deceleration into account. Similar to Larson et al. (2013), they heuristically coordinate neighboring trucks in pairs after setting up a globally optimal platoon formation problem without guaranteeing individual benefits. By using this hybrid speed adjustment approach, even larger savings are shown to emerge than with a mere acceleration-based one. Saeednia and Menendez (2016) also prove a hybrid strategy to be more favorable by comparing an integrated optimization model with solely speeding up or slowing down. After all, platoons can be formed quickest like this.

In Van De Hoef et al. (2015a), the authors specifically mention the "non-trivial trade-off between higher fuel consumption due to increased speed and reduced fuel consumption due to platooning" (Van De Hoef et al., 2015a). For this reason, they introduce both an optimization problem and an approximate algorithm which successfully consider routing as well as velocity-dependent fuel consumption to account for centralized platoon coordination through speed adjustments. Here, the identification of possible convoy configurations is performed after determining each truck's shortest path. A fuel-optimal velocity profile is the result while also abiding by arrival deadlines and speed limits. Furthermore, van de Hoef et al. (2016) attempt to substantially reduce the required computational effort for the dynamic coordination of platoons over larger temporal and geographic instances. A central system is meant to provide respective speed profiles and routes to form convoys. To this end, they successfully develop an algorithm which efficiently focuses on actually feasible platoon configurations by a corresponding rule out mechanism. According to Van De Hoef et al. (2015b), positive impacts on fuel economy can also be generated by coordinating truck platoons based on the determination of fuel-optimal speed patterns in a pairwise manner. A set of PLs is computed via clustering, before PFs adjust their velocities accordingly to merge with the respective clusters' PLs. They give proof to the effectiveness and efficiency of their approach by Monte Carlo simulations and finally conclude that centralized "coordination of platooning is crucial to leverage its full potential to save fuel" (Van De Hoef et al., 2015b).

Unlike all these research contributions, Deng and Ma (2014) take the general adjustment of the vehicles' velocities when already being in a convoy into account. The provision of real time information about traffic conditions from V2V or V2I communication allows to intelligently calculate optimal speed profiles for the PL. From these, the so-called Optimal Speed Planning algorithm subsequently derives the PFs' reactions, leading to suboptimal, but computationally more efficient solutions than those given by the exact dynamic programming model used for comparison. Hence, the intelligent design of speed patterns also during platooning yields significant energy saving potentials as well.

We now want to bridge to another group of platoon coordination studies, focusing more on the combinatorial problem of routing and scheduling.

3.3. Cost-efficient platoon coordination based on centralized routing and scheduling decisions

The joint planning of trips in terms of scheduling and routing before departure acts an important part on the way to make platooning an everyday reality in the transport sector. Be it just for their own fleet or from an inter-company perspective – fleet operators must be supplied with transparent transport cost information to convince them of the benefits which platooning brings with itself, especially at the beginning. SOS as a first stage in its development path, but also major parts of ORP, require solutions to computationally address this urgent topic in the end. To the best of our knowledge, relatively few studies have been published in this young field of platooning research so far. For this purpose, table 2 provides the current state of literature with regard to platoon coordination approaches by planning trips centrally in advance. In general, it must be mentioned that all of the listed publications study platooning-based models on one-way trips from a truck's origin to its destination. At this point in time, the consideration of extensive multi-location tours in terms of Vehicle Routing Problems (VRPs) that take the option of platooning into account is not subject of published research yet.

3.3.1. Platoon planning with Linear Programming approaches

Some progresses have already been made in addressing different issues relating to platooning by Linear Programming (LP) approaches to optimize transport costs. Some authors also provide computationally more efficient heuristics to this end.

By still discarding deadlines and time indices for scaling reasons in their work, Larsson et al. (2015) are the first to formulate a general ILP-based routing problem which they call the (temporally) Unlimited Platooning Problem (UPP). They do not only prove its NP-hardness, but also take different approaches to investigate the fuel-optimal coordination of platoons when such a computational complexity is inherent. Initially, all trucks are meant to start from the same loca-

Table 2: Overview of platoon coordination literature – part 2

Publication	Platooning decision	Formation strategy	Major research contributions
Adler et al. (2016)	before trip, en route	scheduling, waiting	– analytical study based on queueing theory – derivation of pareto-optimal boundary regarding the trade-off between fuel savings due to platooning and arrival delays due to waiting
Larson et al. (2016)	before trip	scheduling, waiting, routing	– MIP formulation for the combinatorial problem of vehicle routing and platoon scheduling – increase of computational efficiency by introducing auxiliary parameters and constraints – effects of waiting at origin and intermediate nodes are investigated
Larsson et al. (2015)	before trip	waiting, routing	– formulation of the platooning problem as an ILP (same & different start locations) – proof of its NP-hardness – best pair & hub heuristic along with local search improvement heuristic for increased efficiency – large real-world instances result problematic
Luo et al. (2018)	before trip	scheduling, waiting, routing, speed selection	– integration of routing, scheduling, individual speed selection and platoon formation / dissolution in a MILP – efficient clustering heuristic which first seperates the set of trucks before routing each group individually
Meisen et al. (2008)	before trip	waiting	– data-mining based heuristic for platoon planning – exponential increase of amount of platoons with amount of trucks / common route segments – pruning parameters required for efficiency
Minner (2017a)	before trip	scheduling, waiting, routing	– introduction of a network flow formulation for platooning – mentions the consideration of driving time regulations and lateness penalties in a platooning environment for future investigations
Nourmohammadzadeh and Hartmann (2016)	before trip	scheduling, waiting, routing	– integration of arrival deadlines into a MIP-based platooning problem – development of an efficient genetic algorithm building upon the prior elimination of impratical routes
Sokolov et al. (2017)	before trip	scheduling, waiting, routing	– comparison of central coordination with an uncoordinated ad hoc approach based on simulations – investigations by means of the MIP formulation by Larson et al. (2016) as a basis – substantial increase of platooning possibilities through reasonable waiting times at origin
Zhang et al. (2016)	before trip	scheduling, waiting	– introduction of platoon scheduling problem considering travel time variance – calculations based on expected cost – takes expected fuel cost, schedule miss penalties and travel time cost into account
Zhang et al. (2017)	before trip	scheduling, waiting	– definition of platoon coordination and departure time scheduling problem under travel time uncertainty – calculations based on expected cost – platooning less favorable on converging compared to diverging routes due to a delayed merging

tion within a same-start UPP, given a set of dispersed destinations. This setting creates larger fuel savings due to the slipstream effect than the original UPP case with different starts and destinations because the trucks do not have to find ways to merge at all before. Furthermore, it is still able to handle bigger instances of up to 200 vehicles in the German Autobahn network, whereas the UPP can only capture up to 10 trucks within a reasonable period of time. For both Platooning Problems (PPs), a specifically defined decision variable decides if a truck – the one with the lowest index in a convoy – is a PL (can also be an individually driving truck) or not. Another one indicates the resultant platoon matchings where the lower vehicle index is assigned to the leading position. Since the two versions of the optimization model are even hard to solve efficiently without the presence of deadlines, they introduce two construction heuristics as well as one improvement heuristic next. The Hub Heuristic divides the original PP into several sub-problems and builds truck partitions which are assigned to a hub. A platoon routing is then found by successively solving truck trips towards their hubs before getting a solution for the further way to their destinations. The Best Pair Heuristic, in contrast, reduces the number of transport missions step-by-step by iteratively merging truck / platoon pairs with the highest current fuel savings potentials. Then, the optimal sets of formation and dissolution nodes are generated which replace the former missions by spanning a single new mission between these nodes. An improving local search based on single path updates finally refines the performance of both construction heuristics. Tests of the optimal approaches strongly underpin the financial benefits of coordinated platooning for small instances while even the heuristics are able to find near-optimal solutions for larger settings in most cases. After all, it must be pointed out that with randomly chosen origin and destination pairs, savings are subject to completely unforeseen platooning opportunities and are thus naturally lower than in case of a same-start environment.

Larson et al. (2016) investigate a very similar combinatorial Mixed-Integer Programming (MIP) formulation instead of "decompos[ing] the platoon coordination and vehicle routing into separate problems" (Larson et al., 2016). Specifically focusing on modern and effective techniques to reduce computational complexity, they do not rely on heuristics, but only introduce efficiency-raising auxiliary constraints and parameters. Among these, a maximum possible deviation from the shortest path or the prior identification of a temporal feasibility to be able to platoon at all can be found, for example. Such measures turn out to significantly decrease the required computational efforts to calculate fuel-optimal solutions.

Building upon the previous work, Sokolov et al. (2017) account for the central coordination of routes as well as departure times and compare this scenario with uncoordinated ad hoc platooning, i.e. the vehicles take their shortest paths and just platoon by chance. They clearly demonstrate the superiority of a coordinated approach, justifying it with planned waiting times which can also allow for longer platooning distances. Since very often "drivers are willing to delay their departures in order to be able to travel in a platoon" (Sokolov et al., 2017) they examine different levels of willingness to wait, but only before departure. Larson et al. (2016), on the other hand, allow idle times at intermediate nodes too, even though without accounting for corresponding costs to study the platoon savings' upper bound. In both cases, waiting for a reasonable amount of time turns out to be advantageous from a financial perspective as this obviously increases the opportunities to platoon. However, as time-dependent costs like wages also have to be taken into account, exceeding a certain threshold waiting time results disadvantageous – particularly at intermediate nodes where drivers are already on the job.

Another extension to the latter two studies is provided by Luo et al. (2018) who additionally consider the selection of speeds in their platoon routing and scheduling approach. For this purpose, they set up a Mixed-Integer Linear Programming (MILP) model called Coordinated Platooning Model with Multiple Speed Options as well as a heuristic based on clustering principles which even exploits low probabilities to platoon by identifying significant differences in origin / destination nodes / times. As mentioned above, the fuel consumption also depends on the respective speed profile of a truck. Hence, this study brings platoon coordination closer to reality – also considering that speed selection can affect the formation and dissolution of train-like convoys. The Coordinated Platooning Model with Multiple Speed Options as a modified version of the MIP in Larson et al. (2016) and the heuristic perform almost equally well for small instances, whereas the latter one outperforms in larger settings due to its computational efficiency.

Similar to Minner (2017a) who proposes an optimal network flow MILP formulation for platooning with earliest possible departure times, Nourmohammadzadeh and Hartmann (2016) include deadlines for latest possible arrival times in their platooning considerations as well. Waiting at any node is also allowed within their model. Nevertheless, they still address the problem of computational complexity by resorting to metaheuristics in terms of a genetic algorithm as well as a pruning constraint related to generally feasible route deviations similar to Larson et al. (2016). Herein, impractical routes are eliminated in an effective evolutionary manner. Minner (2017a), in contrast, highlights different ways to computationally master the issue of larger problem instances. Next to metaheuristics, he also takes stepwise hierarchical planning approaches and rolling horizon planning into consideration which have both not been explored for the PP yet. Perspectively, the notes on unknown impacts of 'soft' travel time windows (with penalties for a later arrival) and compulsory driving time restrictions on platooning provide the basis for future investigations.

3.3.2. Examination of platoons under stochastic and data-mining conditions

In order to specifically gain insights into the impacts of waiting, both Zhang et al. (2016) and their further stochastic elaborations in Zhang et al. (2017) look at platooning from an optimized expected cost framework perspective under varying travel times in simple network structures. Considering penalties for schedule deviations, time-dependent and fuel-related costs, they conclude that potentially long waiting times at merging points make platooning less favorable on converging routes compared to diverging routes. The two studies also prove that differing arrival time schedules lead to a waiting time threshold value which determines if profiting from platooning and arriving on time are conflicting objectives or not. As expected, travel time uncertainty negatively influences the benefits provided by platooning in a significant way.

Two rather specific studies explore platooning from a stochastic queuing theory (see Adler et al., 2016) and data-mining (see Meisen et al., 2008) perspective. The former ones investigate the trade-off between a reduced fuel consumption thanks to platooning and costly waiting times which can cause transport delays. They derive a pareto-optimal fuel-time threshold by applying two different policies for platoon formation: all trucks leaving a location after a defined period of time or after reaching a defined platoon size. By contrast, the latter ones apply a heuristic based on data-mining techniques to organize truck platoons for common route segments by means of waiting. They found out that pruning parameters are required due to the exponentially rising complexity with an increasing amount of trucks or paths in a network. By testing their method on an artificial dataset, preset limits for parameters like common distance, waiting time and possible profits prove efficiency-raising for their calculations.

3.4. Integration of mandatory EU legislation on driving times, breaks and rest periods into routing and scheduling problems

After working out the current state of research in platoon coordination mechanisms and their meaning for routing and scheduling decisions so far, it is now necessary to shed some light on incorporating compulsory breaks and rest periods into the design of cost-efficient tours.

3.4.1. Overview and consequences for platooning-based frameworks

Except from the working paper by Tavasszy (2016) on potential scenarios relating to a task relief when trailing, no study has been published so far which addresses these critical EU restrictions in connection with platooning by more than just a mention, according to our previous investigations. To this end, we review specific literature in a related field of research: namely VRPs under consideration of truck driver scheduling decisions. Most publications in this area deal with the combinatorial problem of the two sub-problems of vehicle routing and truck driver scheduling in the presence of mandatory service time regulations. Since the VRP with time windows alone is already hard to solve efficiently (NP-hard) – and compulsory driving or working time restrictions add even more complexity – literature primarily resorts to different kinds of approximate heuristic algorithms instead of solving such types of problems to global optimality (see Goel, 2009). A comprehensive list of these research contributions in different legal settings – especially in the EU, but also in Australia, Canada and the United States of America – is provided in table 3.

Due to its own computational complexity, the framework of platooning trucks per se has not yet been incorporated into a VRP environment with multiple customer locations, respective time windows, consecutive working activities and a return to the depot yet. Consequently, as we are primarily interested in feasible and intuitive ways to include the characteristics of Regulation (EC) No 561/2006 in our later platooning model, we do not go into further details regarding the different in-depth approaches presented in table 4. We rather intend to focus on the more general aspects which need to be considered in order to ensure an appropriate interaction between the basic ideas behind truck platooning and essential legal driver requirements in the EU. Please note that the specifics of working time restrictions (Directive 2002/15/EC) remain unconsidered within the framework of this thesis, but are meant to be well in line with our modeled rules on driving times.

Some publications provide MIPs with the focus on minimizing the duration of driver schedules, covering the most relevant legal transport frameworks within big truck markets around the world. Goel (2012a), for example, provides a generic version to this end, which can be adapted to different legal settings.

Yet, “European Union regulations have the most restrictive limits” (Goel and Vidal, 2013). Not least also because of the origin of most existing research contributions in this field and the presence of required technological know-how of globally acting European truck manufacturers, it is useful to start here first. Nevertheless, as the concept of platooning makes further progresses, other legal contexts need to be considered within the next years as well.

3.4.2. Specific characteristics of existing research contributions

Kopfer and Meyer (2010) are the first ones to present a precise MILP formulation accounting for the whole range of mandatory EU driving and working time regulations. Within their model, breaks and rest periods are not precisely scheduled at defined nodes like customer locations, freight centers or specific parking lots. They rather leave the decision on where to take a pause to the driver. “The consideration of the locations of suitable rest areas, however, is particularly important if motorways are used and truck drivers must continue to drive until the next appropriate rest area is reached” (Goel, 2012a). As this is one of the most critical aspects for the coordination of platoons as well to allow for a proper composition of convoys at all, driving schedules must be transparent and mutually adapted. Idle times could actually be exploited as times to wait for other trucks, which has been shown to have a positive impact on platooning. Thus, known meeting points play a key role for the in-advance coordination of highway-based platooning.

Fleet managers need to be flexible – and the introduction of platooning will not change this critical requirement. As pointed out in chapter 2, there exist various modifications besides the basic rules which provide a certain freedom of choice to the decision where, when and how breaks or rest periods are taken. Unknown traffic conditions, accidents or other unforeseeable circumstances can make these options indispensable for not getting into serious economic pressure. But they could also have a very positive impact on merging maneuvers when it comes to meeting another truck’s respective time schedule. Although “there are strong incentives for European motor carriers to exploit all optional rules of the regulations, in particular, reducing the duration of rest periods and extending driving times” (Goel and Vidal, 2013), considering them in scheduling decisions increases the computational effort as well. Moreover, especially the last-named options cannot be exploited on a regular basis and are thus only of conditional interest for a platooning model with a relative short planning horizon like those presented in the previous sections. Hence, an increased level of robustness can be achieved without including the entire set of special rules (see Goel, 2009; Goel, 2010; Goel and Vidal, 2013; Kok et al., 2010).

As far as the decision whether to deploy one or two truck drivers on a trip is concerned, Kopfer and Buscher (2015) already identified the lack of investigations in this regard and finally of its inclusion into tour planning. They perform a comparative productivity analysis on the application of these two operating modes and conclude that the required driving (and working) hours of a transport task primarily determine the manning decision. Since a team of drivers needs less time for a trip – but at the cost of double wages – extraordinarily narrow time windows could also call for this alternative. While Meyer and Kopfer (2008) only discuss theoretical implications of (not) applying mandatory rules with regard to single or double manning, Goel and Kok (2012b) just focus on scheduling double-manned trucks. To the best of our knowledge, no further publications address this aspect at all in cost-efficient tour planning, not to mention in a platooning context. However, we have already demonstrated in

Table 3: Overview of truck driver scheduling literature

Publication	Legal setting	Manning	Regulated scope	Applied rules	Planning horizon	Major research contributions
Archetti and Savelsbergh (2009)	USA	single	driving times	most important rules in the USA	< 1 week (starting on Monday)	– backward search algorithm for the trip scheduling problem under consideration of mandatory driving time restrictions – sequence of full truckload transportation requests and respective dispatch windows – feasible dispatch schedule (if at all existing) in polynomial time
Bernhardt et al. (2016)	EU	single	driving times	standard rules break / rest period splitting driving time extension rest period reduction	< 1 week (starting on Monday)	– extensive MILP model and myopic algorithm to schedule driver activities based on a given sequence of customer locations to be visited and mandatory driving time rules – one or multiple time windows at each location – consideration of soft time windows and specific status constraints for the driver
Goel (2009)	EU	single	driving times	standard rules	< 1 week (starting on Monday)	– large neighborhood search algorithm for the generation of vehicle tours based on a given sequence of customer locations with respective time windows to be visited – naive and multilabel methods for scheduling purposes under mandatory legislation – description of the driver's state in terms of a multidimensional label
Goel (2010)	EU	single	driving times	standard rules break / rest period splitting	< 1 week (starting on Monday)	– breadth-first search algorithm which guaranteedly finds a feasible driver schedule (if at all existing) for a given tour in the presence of time windows for multiple customer locations to be visited, considering mandatory driving time restrictions – significant reduction of computational effort possible by prohibiting break splitting
Goel (2012a)	EU, USA	single	driving & working times	standard rules in the EU (notes on inclusion of optional rules), most important rules in the USA	not specified	– generic MIP formulation for the truck driver scheduling problem which can be configured flexibly according to diverse international service time regulations – fixed sequence of customer locations with multiple time windows to be visited – dynamic programming-based solution approach is presented
Goel (2012b)	AUS	single	driving & working times	most important rules in Australia	< 1 week (starting on Monday)	– MIP formulation to minimize the duration of truck driver schedules – significant reduction of computational effort possible by introducing specific inequalities into the model with mandatory driving and working time restrictions – multiple customer locations to be visited within their respective time windows
Goel (2012c)	CAN	single	driving & working times	most important rules in Canada	< 1 week (starting on Monday)	– MIP formulation to minimize the duration of truck driver schedules – faster iterative dynamic programming approach (at the cost of slightly longer schedule durations in the presence of mandatory service time regulations) – multiple customer locations to be visited within their respective time windows
Goel and Gruhn (2006)	EU	single	driving times	standard rules	< 1 week (starting on Monday)	– large neighborhood search algorithm-based solution approach for a generalization of the VRPTW, which is restricted by mandatory driving time regulations
Goel and Kok (2012a)	USA	single	driving & working times	most important rules in the USA	< 1 week (starting on Monday)	– scheduling method which guarantees to find a feasible truck driver schedule (if at all existing) under consideration of a sequence of customers with given time windows and mandatory service time restrictions
Goel and Kok (2012b)	EU	double	driving times	standard rules driving time extension	< 1 week (starting on Monday)	– depth-first-breadth-second search algorithm for the purpose of finding a feasible driver schedule (if at all existing) for double-manned trucks in the presence of mandatory driving time restrictions – multiple customer locations to be visited within their respective time windows
Goel and Rousseau (2012)	CAN	single	driving & working times	most important rules in Canada	< 1 week (starting on Monday)	– exact scheduling algorithm for the truck driver scheduling problem in the presence of time windows for multiple customer locations to be visited – comparison with two (faster) heuristics considering mandatory driving and working time regulations
Goel and Vidal (2013)	AUS, CAN, EU, USA	single	driving & working times	standard and optional rules in the EU, most important rules in Australia, Canada and the USA	< 1 week (starting on Monday)	– hybrid genetic algorithm with advanced diversity control for fleet routing and scheduling purposes under consideration of international on duty time regulations and given customer time windows – assessment and comparison of the respective international rules' economic impact
Kok et al. (2010)	EU	single	driving & working times	standard rules break / rest period splitting driving time extension rest period reduction	< 1 week (starting on Monday)	– restricted dynamic programming heuristic for the VRPTW which includes a break scheduling heuristic to account for mandatory driving and working time regulations in road transport – exploitation of modified / optional rules leads to favorable cost efficiencies
Kok et al. (2011)	EU	single	driving times	standard rules break splitting	< 1 day (incl. notes on multi-day planning)	– ILP-based departure time optimization problem as a post-processing step for the solution of the VRPTW in the presence of mandatory social legislation on driving times – multiple customers to be visited under consideration of time-dependent travel times due to changing traffic conditions
Kopfer and Buscher (2015)	EU	single & double	driving & working times	standard rules	not specified	– presentation of a quantitative cost function for the deployment of vehicles and their drivers under consideration of mandatory driving and working time restrictions – productivity analysis with regard to the choice of the respectively applied operating modes (single vs. double manning)
Kopfer and Meyer (2010)	EU	single	driving & working times	standard rules break / rest period splitting driving time extension rest period reduction	< 1 week (starting on Monday)	– position-oriented formulation of a VRPTW-based MIP model, including mandatory EU driving and working time regulations (VRPTW-EU) – first full optimization model to exploit the whole range of on duty time restrictions
Meyer and Kopfer (2008)	EU	single & double	driving & working times	standard rules break / rest period splitting driving time extension rest period reduction	not specified	– discussion of the mandatory driving and working time restrictions' influence on truck routing and the fundamental consequences of ignoring them in the planning process – consideration of different interconnected time horizons – general aspects of modelling specific rules are presented
Meyer (2011)	EU	single	driving & working times	not specified	not specified	– inclusion of the VRPTW into a framework of distributed (hierarchical) decision making while considering mandatory social truck driver legislation – based on mutual anticipation functions
Minner (2017b)	EU	single	driving times	breaks only (incl. splitting)	not specified	– MIP formulation with mandatory break time regulations as an extension to the standard TSP – clock variable to track the accumulated driving time up until the next required break
Prescott-Gagnon et al. (2010)	EU	single	driving & working times	standard rules break / rest period splitting driving time extension rest period reduction	< 1 week (starting on Monday)	– large neighborhood search method for the VRPTW with mandatory driver regulations – use of a tabu search-based column generation heuristic for the dynamic generation of routes and a heuristic labeling algorithm to check the routes' feasibility
Xu et al. (2003)	USA	single	driving & working times	most important rules in the USA	< 1 week (starting on Monday)	– column generation-based solution approaches with fast heuristics for subproblems of the pickup and delivery VRP under consideration of mandatory driving and working time restrictions – multiple time windows at each customer location to be visited

chapter 2 that manning options are also interrelated with the theoretically possible task-relieving effects of exploiting the PL's slipstream and the decision to platoon. So, advances in this regard are also of strong economic and political interest. Please note that we will not take double manning justified by extreme temporal restrictions into account.

In order to be able to decide upon a next required break or rest period at all, different approaches are chosen by the various authors. On the one hand, Bernhardt et al. (2016) set up an extensive MILP model specifically accounting for the driver's status. This results in a large number of constraints and high mathematical complexity in light of all the future activities that need to be performed within a VRPTW – a framework which has not been addressed yet for the topic of platooning. Other authors sum up the task times needed between a number of locations and check if a given temporal limit is exceeded, but without separately considering the individual driver's status (see for example Goel, 2012a; Kopfer and Meyer, 2010). On the other hand, Minner (2017b) introduces the idea of a 'clock variable' for breaks which keeps track of the accumulated driving time so far, moving from one node to the next within a Travelling Salesman Problem (TSP). As soon as such a compulsory pause needs to be taken, this status-like variable is reset to zero again and starts counting anew. Compared to the other models, its separate calculation of a status after travelling each single edge between two nodes allows to consider both ascending and descending node indices within computations. Next to this advantage, the latter approach also seems favorable for an application in a platooning environment where potential task reliefs for trailing come into play. Herein, the differentiation between the real driving time and the potentially lower, actually charged driving time is key to decide upon platooning.

Considering all these insights about the meaning of distinct rest areas, optional pause time rules, the inclusion of manning decisions and finally the way of handling mandatory driving time regulations in a certain context at all, we are now able to derive a proper basis for our EU law-based platooning approach.

3.5. Summary of literature and research findings

Summing up, it can be concluded that central coordination will be indispensable for the design of cost-efficient tours for trucks by means of platooning – be it in terms of a PSP or a virtual planning tool for fleet operators. Particularly during the early phases of platooning when still relatively few trucks will have the respective technological equipment, jointly scheduled departure times, breaks, rest periods and arrivals are of great importance. "If platooning opportunities are present, the routes may differ slightly from the obvious shortest path routes, in order to maximize fuel savings" (Larsson et al., 2015). So, also routing aspects need to be specifically addressed when deciding upon formation and dissolution.

The findings in section 3.3 reveal how important off-road transportation planning before departure can actually be to exploit the full range of benefits from truck platooning. Nevertheless, the above reviewed studies demonstrate that focusing on velocity profiles on-road can heavily enhance the opportunities to platoon – ultimately leading to reduced freight transport costs. Herein, the combination of catch up and slow down maneuvers (i.e. a hybrid strategy) of the PFs and the PLs respectively prove most advantageous. Such research contributions will pave the way for OTFP applications in the future. The additional complexity herein though results from a speed-dependent and acceleration-influenced fuel consumption of the vehicles, which most of the aforementioned authors still leave aside. Moreover, it is hardly possible for carriers to anticipate their trucks' speed profiles to base their fleet management upon before a trip. This has several reasons. On the one hand, such catch up or slow down maneuvers are often coordinated regionally by local controllers (see for example Larson et al., 2013), being also affected by unknown traffic conditions. On the other hand, this inherent lack of transparency makes overall cost structures intangible. Thus, a rough cost and savings indication through platooning is clearly desirable – especially when OTFP is still farther from implementation than virtual platform-based SOS or an ORP approach managed by an orchestrating PSP. A transparent platoon coordination tool based on comparatively reliable key trip data could provide remedy for this purpose. This estimation is supported by the fact that carefully planning mandatory breaks and daily rest periods is critical for fleet operators as well, which we want to particularly address within the framework of this thesis. So, even though utilizing speed as a means for forming convoys throughout a journey will undoubtedly display platooning's entire potential in the end, we recommend that exploiting in-advance platoon coordination should currently be the first choice to create cost efficiency.

LP-based modeling approaches like those presented by Larsson et al. (2015) and Nourmohammadzadeh and Hartmann (2016) turn out to be appropriate for further extensions. Although they still bear limitations with respect to the size of problem instances and computational complexity, problems can be solved to optimality and thus be well used as a reference for simplistic, but faster heuristics or applied standard planning scenarios in the EU without platooning. Moreover, they are able to indicate the upper bound of overall possible cost savings generated by platooning – giving reason to further research in this field to promote this new technology. Such optimization problems are still based on trips from one origin to one destination, i.e. one-way without multiple stops at intermediate customer locations with respective time windows to be met. Thus, it seems advisable to base the next step of investigations upon a relatively short planning horizon within this thesis as well, before future research extends this context to a more complex one then.

As the basic UPP without any temporal restrictions is already NP-hard in itself, the issue of handling this kind of complexity is omnipresent in the reviewed literature. Furtherly extending the framework of platooning will thus rather increase the complexity of such a setting – and consequently the need for smart solutions – than decrease it. Pruning the PP by a maximum feasible deviation from the shortest path as performed by Larson et al. (2016) and Nourmohammadzadeh and Hartmann (2016) results efficiency-raising. But even if auxiliary constraints or other pruning methods perform well when it comes to increasing the number of trucks and nodes as well as the computational performance within numerical studies, approximate and simplified heuristics are indispensable to deliver (sub)optimal results in a reasonable amount of time. Therefore, promising approaches have been proven by literature to be well applicable to the PP, but further new ideas need to be taken into account when exploiting the characteristics of this problem type. Hierarchical planning can be one of many ways to do so, as also mentioned by Minner (2017a).

A combinatorial framework for routing and scheduling a truck from its origin to its destination in the presence of platooning opportunities should contain the possibility to wait for each other. The above research contributions proved the positive effect which waiting can have on the possibilities to platoon. Be it at the origin before departure or at a stopover during the trip – such pauses can have an increasing effect on the distances travelled in a convoy at a respective trade-off between achievable fuel savings from platooning and additional personnel cost from waiting. Already mandatory waiting times like those breaks and rest periods stipulated by the EU could result favorable, but also impeding in this regard.

In order to include them into our social transport law-restricted platooning model, we need to consider distinct rest areas for the trucks' coordination. These can then be used as meeting points to facilitate platoon merging maneuvers through smart routing and scheduling decisions.

Furthermore, 'clock variables' or 'timers' turn out to be suitable for the ability to track the status of truck drivers at all. This becomes even more important if politics decides in favor of a certain task-relieving share for following drivers in a platoon. Since the legally charged driving time would differ from the actual driving time on the road, such an indication is highly desirable for the calculation of potentially updated breaks or daily rest periods in the presence of platooning.

Along with this aspect comes the need for specific decision variables like those in Larsson et al. (2015) to consider the respective truck's position within a platoon. These are not only helpful for the computation of potential platoon configurations between the trucks, but also seem promising to be exploited for the (re)calculation of the involved drivers' status where the assigned roles act an important part.

In the end, manning options can have a leverage effect on platooning as already shown in chapter 2. The lack of corresponding literature and their large economic impact on transport companies call for their consideration in platoon planning.

Next to the standard application of breaks and daily rest periods within the framework of Regulation (EC) No 561/2006, some of its flexibility-increasing possibilities might also favor our coordination approach. When exploiting optional rules like pause time splitting, extended driving times or reduced rest periods, a balance between rising model complexity and extra value added through more necessary flexibility must be found though. Since break and daily rest period splitting can be applied on a regular basis, these turn out to be more appropriate. Platooning could actually profit from these options as the respectively required idle times of truck drivers can be reconciled more easily by joint scheduling then.

The inclusion of lateness penalties to allow for slight schedule deviations as done by Zhang et al. (2016) could also provide more flexibility to the fleet managers when planning their trips. Contrasting the advantages of such 'soft' time windows with possible fuel savings from platooning can potentially lead to different scheduling decisions in the end.

Finally, figure 6 gives a summarizing overview of the most important modeling ingredients from literature that we consider appropriate for our research purposes.

Having identified the essentials of bringing platooning one step closer to implementation from valuable insights into current research, we are now able to present our mathematical modeling approaches to address the consideration of Regulation (EC) No 561/2006 within the context of truck platooning, along with its potential legal amendment relating to a task-relieving effect from trailing as a PF.

4. Models, Heuristics and Implementation

This chapter presents a platooning-based optimization problem for cost-efficient road transportation in the EU. In this this regard, we develop an exact solution approach and address the issue of computational efficiency by introducing two hierarchical planning-based matheuristics as well as further efficiency-raising measures. Besides, two benchmark models for our later experiments are provided. Please see Appendix A for a reference to the respectively implemented models.

4.1. The EU-Truck Platooning Problem (EU-TPP)

The following elaborations serve to provide and extend the basis for the problem of platoon coordination based on SOS and parts of ORP as first important stages on the promising platooning concept's way into the transport market. Resting upon the current status of literature and research, we formulate an ILP-based exact model which we call the EU-Truck Platooning Problem (EU-TPP), considering mandatory regulations on driving times, breaks and daily rest periods in the EU as well as a hypothetical task-relieving effect for trailing in the slipstream of a preceding truck. Before actually introducing the mathematical formulation, we point out the specific features of the model along with its underlying assumptions and define the necessary elements. Please note that the entire model in its compact form is provided in Appendix B.

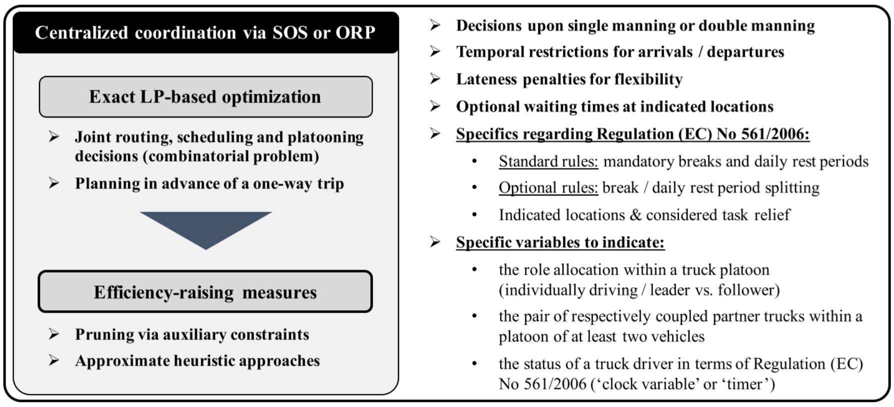

Figure 6: Suggested framework of appropriate coordination characteristics

4.1.1. Characteristics and underlying assumptions

As a basis for our EU-TPP formulation, we use a modified version of the basic platooning concept presented by Larsson et al. (2015). Their ILP model with special variables to indicate the respective platoon constellation and leading vehicles is well applicable to show the impacts of driving in a convoy on fuel economy and delivers promising results. However, we shorten its formulation by removing auxiliary constraints and variables which become redundant as soon as a time index is introduced. Since we need to account for real-world temporal restrictions when including Regulation (EC) No 561/2006, such an index is used to determine the respective truck schedules. Therefore, we also extend this approach by earliest feasible departure and latest possible arrival times to integrate time windows.

Nourmohammadzadeh and Hartmann (2016) and Minner (2017a) provide the corresponding basic principles to do so. Moreover, the EU legislation on mandatory driving times, breaks and rest periods is incorporated by means of status-tracking clock time variables. We make use of their specifics to also consider the potentially task-relieving effect of trailing in a platoon and to set required pauses accordingly. Next to the daily standard rules for both manning options, our approach also takes some optional regulations into account. As we specifically want to further investigate the impacts of platooning on trips from one origin to one destination (no extensive VRPs, i.e. following the current state of platooning research) and thus look at a small planning horizon, only splitting rules are exploited. We recommend to ignore further options like driving time extensions and reduced rest periods in this context. Their irregular applicability together with a presumed increase in computational effort decrease their value added for our approach.

Penalties for arriving after a given deadline are considered as well. These become important when time windows are very narrow and there is no time for optional waiting on the way to platoon. As suggested by literature, waiting at the origin or at intermediate nodes can enhance the opportunities to platoon though. So we also allow for additional waiting stopovers, despite the existence of anyway compulsory idle times in our model which could, in turn, have a restricting character for platoons to be formed. The respective pause locations are indicated as well.

Finally, we take realistic parameter values for speed, fuel and AdBlue cost, truck-specific fuel consumption and truck driver wages into account to calculate the distance-dependent fuel as well as the time-dependent personnel cost. According to our state of knowledge, no other study's results in published platooning research is based on such real-world values so far – especially personnel cost have been widely disregarded. Yet, they represent a major portion of transport cost and thus need to be considered in a platooning context, too. In the end, they can influence the decision whether to wait for another vehicle to platoon or whether to accept a detour for this purpose.

All in all, the following assumptions underlie our exact EU-TPP model:

- All tour information (i.e. origin with earliest possible departure times, destination with latest possible arriving times etc.) is known in advance.
- All trucks travel at the same constant highway speed, i.e. distances between the nodes of the network can also be indicated as fixed time steps.
- All edges (i.e. the connections between two nodes) have the same length.
- The fuel reduction rate is constant and equal among all trailing trucks, i.e. all vehicles share comparable specifications (e.g. in terms of dimensions, loading, engine power etc.), the slipstream gap between trucks within a convoy remains stable (no evasive maneuvers or other disturbances caused by surrounding traffic) and their amount as well as the single trucks' positions inside the platoon do not matter.
- Other influence factors on fuel consumption (e.g. road topography, driving behavior etc.) are negligible, i.e. fuel use remains constant.

- Only the PFs benefit from an increased fuel economy due to platooning, i.e. there is neither a compensation nor a fuel saving effect for the PL.
- It is allowed to participate in more platoons throughout the trip.
- Trucks with lower vehicle indices take the leading position, i.e. trucks with a lower fuel consumption should get a smaller index to allow for higher cost savings from those PFs exhibiting a higher fuel usage.
- The personnel cost per driver, lateness penalty cost as well as the prices per liter of fuel and AdBlue are constant and the same for each truck.
- All truck drivers start their service after a weekly rest period (i.e. at the beginning of the week).
- Breaks, daily rest periods and additional waiting times can only be taken after arriving at a specific predetermined location.
- If additional stopovers are planned to wait for each other to platoon, their duration is not considered as an already taken fraction of mandatory pause times of any type.
- If it makes no difference for platooning opportunities whether to split a break or not, either way is allowed and pauses can be taken at any time before the respective limit of accumulated driving is finally reached.
- Travel time uncertainty (e.g. due to unknown traffic conditions) is not considered.
- Tolls as the third largest impact factor on transport cost (see Wittenbrink, 2011, pp. 1-46) and other smaller TCO components are not considered, i.e. possibly more cost-effective detours apart from platooning-capable highways are not involved in the decision making process.

4.1.2. Definition of sets, parameters and decision variables

In order to formulate our mathematical model, we need to define the necessary sets, parameters and decision variables first.

All vehicles $V = \{1..v\}$, being manned with $M = \{1..m\}$ truck drivers, are assumed to travel in an undirected road network with $N = \{1..n\}$ nodes as locations for cities, customers, rest areas or truck parkings. Additionally, let us assume that the planning horizon$T = 1..t$ is divided into discrete time steps of 15 min each. This interval length has also been chosen by many other authors in truck driver scheduling literature (see for example Goel, 2012a; Goel and Rousseau, 2012) and turns out to be appropriate as all temporal restrictions of Regulation (EC) No 561/2006 can be represented as multiples of this step size.

Basic trip information in terms of individual origins ori_v, destinations des_v, earliest possible departure times ed_v and latest possible arrival times la_v is provided and processed before the start of the tour. The required driving time to cover an edge (i,j) between two locations$i \in N$ and $j \in N$ is given by $d_{i,j}$ and could also be calculated separately by dividing the distance by the respective speed. While c stands for fuel and AdBlue cost per liter, the truck-specific fuel consumption per unit distance (i.e. converted to time steps accordingly) is denominated by f_v. The platooning cost factor η indicates the reduced fraction of fuel use which a truck can benefit from when trailing as a following vehicle behind a PL. Depending on the deployed number of drivers per truck, the personnel cost p_m per time step represent another important trip cost component. As the last financial parameter, pen indicates the penalty cost per additional time step of arriving at the respective destination after the given deadline. Applying the underlying set of compulsory manning-dependent restrictions for a short planning horizon of less more than a day, Regulation (EC) No 561/2006 starts with prescribing a minimum break time $min1_m$ after a maximum accumulated driving period $max1_m$. Moreover, accumulating a an even larger maximum amount of daily driving time $max2_m$ requires a much longer minimum daily rest period $min2_m$. Optional pause time splitting leads to a shorter first part of a mandatory break $brp1_m$ or daily rest period $drp1_m$. Their necessary second parts are then calculated by respectively subtracting a reduction factor $redbr_m$ or $reddr_m$ for breaks and rests from their standard minimum durations. Accounting for a task-relieving effect from platooning in terms of less charged driving times when trailing as a PF, parameter share ensures an adequate calculation of actually charged driving time in accordance with the aforementioned EU law. The last parameter which we introduce here is BIG – a sufficiently large number to simply fulfill a set of inequalities which is often referred to as ‘Big-M’.

In order to design and schedule cost-efficient tours, the binary decision variable $x_{v,i,j,t,m}$ needs to determine whether a vehicle v with m drivers covers sub-route (i,j) on its trip, departing from location i at time t. This routing an scheduling decision is made along with the binary decision upon trucks v and u simultaneously traversing the same edge (i,j) in a platoon $pl_{v,u,i,j,t}$ to save fuel or not. Another binary decision variable $\alpha_{v,i,j,t,m}$ is used to indicate whether vehicle v, being manned with m truckers, takes the leading position / drives individually on this arc without the possibility to save fuel from time t on or enjoys the fuel saving benefits from being a PF. The amount of m truck drivers aboard also influences all the subsequent values. While $a_{v,i,m}$ stands for the integer decision variable which determines the arrival time of truck v at location i, the integer variable $w_{v,i,m}$ decides upon an additional, potentially favorable waiting time of vehicle v at node i. A penalized, delayed arrival of truck v at its destination after its temporal deadline is denoted discretely by $late_{v,m}$.The binary decision variables $fifmin_{v,i,m}$, $thrhour_{v,i,m}$, $br_{v,i,m}$ and $dr_{v,i,m}$ specify whether a first part of a break, first part of a daily rest period, a full or second part of a break as well as a full or second part of a daily rest period is taken by truck v at location i respectively. The duration of a full or second part of a break or daily rest period at node i is indicated by the integer variables $dbr_{v,i,m}$ and $ddr_{v,i,m}$ for each vehicle v. In order to help setting these last-mentioned pauses correctly, the integer decision variables $brClock_{v,i,m}$ as well as $drClock_{v,i,m}$ are used as clocks to track the respective driver's status at node i. Similarly, the binary decision variable $FIF_{v,i,m}$ signals if a shorter first part of a break has already been taken at some node before location i to make sure that the respective second part of a break is scheduled according to EU law. $THR_{v,i,m}$ has the same function for daily rest periods. Based on all these definitions, we can now describe the exact EU-TPP mathematically.

4.1.3. Mathematical formulation

In the objective function below, we seek to minimize the overall transport cost occurring for all trucks v with m drivers in the road network which cover the respective distances between locations i and j during the entire planning horizon T. These total trip cost are subdivided into three major blocks: total fuel cost, total personnel cost and total penalty cost.

$$\begin{aligned}\text{Minimize } Z = \sum_{v\in V}\sum_{i\in N}\sum_{j\in N\setminus i}\sum_{t\in T}\sum_{m\in M} c * f_v * d_{i,j} \\ * \left(\alpha_{v,i,j,t,m} + \eta * \left(x_{v,i,j,t,m} - \alpha_{v,i,j,t,m}\right)\right) + \sum_{v\in V}\sum_{m\in M} p_m * \\ (a_{v,des_v,m} - \sum_{j\in N\setminus ori_v}\sum_{t\in T} x_{v,ori_v,j,t,m} * t) + \sum_{v\in V}\sum_{m\in M} pen * late_{v,m}\end{aligned} \tag{1}$$

The time-dependent personnel and penalty cost components are computed as the product between, on the one hand, the elapsed time between the trucks' respective departures from and arrivals at their origin / destination locations or the particular periods of delayed arrival, and their corresponding cost factors per time unit on the other hand. As regards the more interesting distance-dependent fuel cost block though, we multiply the fuel price and the truck-specific consumption behavior with the actually covered route segments' duration while also considering the characteristic reduced fuel consumption for non-leading vehicles in a platoon.

The following constraints need to be fulfilled to solve the EU-TPP to optimality:

subject to

$$\begin{gathered}\sum_{i\in N\setminus\{des_v\}}\sum_{t=ed_v}^{la_v} x_{v,i,j,t,m} = \sum_{i\in N\setminus\{ori_v\}}\sum_{t=ed_v}^{la_v} x_{v,j,i,t,m} \\ \forall v\in V; j\in N\setminus\{ori_v, des_v\}; i\neq j; m\in M\end{gathered} \tag{2}$$

The flow conservation constraint ensures that each truck entering an intermediate node at a certain time step also needs to leave this node again.

$$\sum_{j\in N\setminus\{ori_v\}}\sum_{t=ed_v}^{la_v}\sum_{m\in M} x_{v,ori_v,j,t,m} = 1 \quad \forall v\in V \tag{3}$$

Each truck starts its tour at its respective origin node within the time interval of its earliest possible departure and latest possible arrival time.

$$\sum_{i\in N\setminus\{des_v\}}\sum_{t=ed_v}^{la_v}\sum_{m\in M} x_{v,i,des_v,t,m} = 1 \quad \forall v\in V \tag{4}$$

Each truck finishes its journey at its respective destination node within the time interval of its earliest possible departure and latest possible arrival time.

$$ed_v \leq \sum_{j\in N\setminus ori_v}\sum_{t\in T}\sum_{m\in M} x_{v,ori_v,j,t,m} * t \quad \forall v\in V \tag{5}$$

This constraint forces each vehicle to start its trip from its respective origin location only after its earliest possible departure time. The choice of the index t sets t as a multiplier for the binary decision variable $x_{v,ori_v,j,t,m}$ and thereby starts a truck's tachograph.

$$a_{v,des_v,m} - late_{v,m} \leq la_v \quad \forall v\in V, m\in M \tag{6}$$

Each truck is supposed to arrive at its respective destination location before its latest possible arrival time. However, if platooning opportunities turn out to be more attractive from a financial point of view than incurred penalty cost of arriving later, the integer decision variable $late_{v,m}$ allows for a deviation from this deadline (i.e. 'soft' time windows are considered).

$$\begin{gathered}\sum_{i\in N}\sum_{t\in T} x_{v,i,j,t,m} * (t + d_{i,j}) \leq a_{v,j,m} \\ \forall v\in V; j\in N; i\neq j; m\in M\end{gathered} \tag{7}$$

A truck's arrival time at the next location is determined by its prior departure from the previous location plus the respectively required driving time in between.

$$\begin{gathered}a_{v,i,m} + dbr_{v,i,m} + ddr_{v,i,m} + brp1_m * fifmin_{v,i,m} + \\ drp1_m * thrhour_{v,i,m} + w_{v,i,m} \leq \sum_{j\in N\setminus\{ori_v\}}\sum_{t\in T} x_{v,i,j,t,m} * t \\ \forall v\in V; i\in N\setminus\{ori_v, des_v\}; i\neq j; m\in M\end{gathered} \tag{8}$$

Each truck can only leave from an intermediate node to the next one after its arrival time and, if applicable, after an additional mandatory break, daily rest period, first or second part of a break or daily rest period or an optional waiting time.

$$\begin{gathered}2 * pl_{v,u,i,j,t} - (\sum_{m\in M} x_{v,i,j,t,m} + \sum_{n\in M} x_{u,i,j,t,n}) \leq 0 \\ \forall v,u\in V; u<v; i,j\in N; i\neq j; t\in T\end{gathered} \tag{9}$$

If two trucks v and u traverse the same edge (i,j) at the same time, the binary platooning decision variable $pl_{v,u,i,j,t}$ is set to one, meaning that both vehicles are in a platoon. Here, the smaller vehicle index is given to the second index position to help determine the PL out of the two trucks in the next constraint.

$$\sum_{m \in M} \alpha_{v,i,j,t,m} \geq pl_{u,v,i,j,t} \quad \forall v,u \in V; v < u; i,j \in N; i \neq j; t \in T \tag{10}$$

This constraint enforces the convention that only the truck with the lower vehicle index can take the role of a leader in a platoon. If $pl_{u,v,i,j,t}$ is true, then the other binary decision variable $\alpha_{v,i,j,t,m}$, which indicates whether truck v is either a PL / an individually driving vehicle or a PF, needs to be set true as well.

$$\sum_{m \in M} \alpha_{v,i,j,t,m} + \sum_{u=1}^{v-1} pl_{v,u,i,j,t} \geq \sum_{m \in M} x_{v,i,j,t,m} \quad \forall v \in V; i,j \in N; i \neq j; t \in T \tag{11}$$

Both binary constituents on the left side of the above inequality cannot and must not be true at the same time due to their index arrangement. However, this specific restriction forces one of them to be true if truck v actually travels from node i to node j.

$$\alpha_{v,i,j,t,m} \leq x_{v,i,j,t,m} \quad \forall v \in V; i,j \in N; i \neq j; t \in T; m \in M \tag{12}$$

Finally, this constraint allows $\alpha_{v,i,j,t,m}$ to be set to one only if truck v traverses edge (i,j) at all. No edge traversal automatically leads to $\alpha_{v,i,j,t,m}$ being zero.

$$\begin{aligned} & brClock_{v,i,m} + d_{i,j} * \\ & \sum_{t \in T} \left(\alpha_{v,i,j,t,m} + share * \left(x_{v,i,j,t,m} - \alpha_{v,i,j,t,m} \right) \right) - \\ & BIG * \left(1 - \sum_{t \in T} x_{v,i,j,t,m} \right) - BIG * br_{v,j,m} - \\ & BIG * dr_{v,j,m} \leq brClock_{v,j,m} \\ & \forall v \in V; i,j \in N; i \neq j; m \in M \end{aligned} \tag{13}$$

In order to track a truck driver's respective status with regard to mandatory breaks, the specifically introduced clock variable must be set correctly between two consecutive nodes i and j. After leaving a location with an initial status of $brClock_{v,i,m}$ on the timer, the required driving time $d_{i,j}$ to reach the next location is added to set the new status $brClock_{v,j,m}$ there. However, if the respective truck v is a trailing truck and the EU political authorities decide upon a task-relieving effect when being a PF, only a fraction share of the actual driving time is charged as theoretical and legally official driving time in view of Regulation (EC) No 561/2006. There are three Big-M components included in this constraint. The first one sets the clock to zero when there is no traversal of truck v on arc (i,j) from time t on, whereas the last two make sure that the break clock is reset as soon as either a break or a daily rest period is taken. The Big-M needs to be sufficiently large and must be chosen appropriately for this purpose.

$$\begin{aligned} & drClock_{v,i,m} + d_{i,j} \\ & * \sum_{t \in T} \left(\alpha_{v,i,j,t,m} + share * \left(x_{v,i,j,t,m} - \alpha_{v,i,j,t,m} \right) \right) - \\ & BIG * \left(1 - \sum_{t \in T} x_{v,i,j,t,m} \right) - BIG * dr_{v,j,m} \\ & \leq drClock_{v,j,m} \forall v \in V; i,j \in N; i \neq j; m \in M \end{aligned} \tag{14}$$

This constraint enforces the same principles for mandatory daily rest periods as the previous restriction does for breaks – with the only difference that the rest period clock is not reset when a compulsory break is taken.

$$\begin{aligned} & max1_m - brClock_{v,i,m} - \\ & d_{i,j} * \sum_{t \in T} \left(\alpha_{v,i,j,t,m} + share * \left(x_{v,i,j,t,m} - \alpha_{v,i,j,t,m} \right) \right) \geq 0 \\ & \forall v \in V; i,j \in N; i \neq j; m \in M \end{aligned} \tag{15}$$

Whether a mandatory break is required or not is finally determined in this restriction. While also taking the driving time to the next node j into account (which is potentially less charged for a PF who is trailing from a legal point of view), the current driver status at node i is deducted from the maximum accumulated driving time limit until a break becomes necessary. If this limit would be exceeded on the way to the next node – i.e. the above constraint would be unfulfilled – the mandatory break still needs to be taken at the current location i. The break clock is reset as a consequence and the above constraint is fulfilled again.

$$\begin{aligned} & max2_m - drClock_{v,i,m} - \\ & d_{i,j} * \sum_{t \in T} \left(\alpha_{v,i,j,t,m} + share * \left(x_{v,i,j,t,m} - \alpha_{v,i,j,t,m} \right) \right) \geq 0 \\ & \forall v \in V; i,j \in N; i \neq j; m \in M \end{aligned} \tag{16}$$

This constraint enforces the same principles for mandatory daily rest periods as the previous restriction does for breaks.

$$\begin{aligned} & FIF_{v,i,m} + fifmin_{v,i,m} + BIG \\ & * \left(1 - \sum_{t \in T} x_{v,i,j,t,m} \right) \geq FIF_{v,j,m} \\ & \forall v \in V; i,j \in N; i \neq j; m \in M \end{aligned} \tag{17}$$

Here, the information whether a first part of a mandatory break is taken at location i is conserved by $FIF_{v,j,m}$. So if $fifmin_{v,i,m}$ is true, then variable $FIF_{v,j,m}$ is set true as well because of the additional constraint (22) where it seeks to be high in order to keep the financially charged break time $dbr_{v,i,m}$ as low as possible. The binary decision variable unfolds its effect at the next location j then, where information on a preceding first part of a break is required to decide upon a potential second part. As $fifmin_{v,i,m}$ is also associated with cost, no further first part of a break would be scheduled as long as $FIF_{v,i,m}$ is still true. The partial break conservation is irrelevant for non-consecutive nodes (i.e. if $x_{v,i,j,t,m}$ is set false).

$$FIF_{v,j,m} \leq \left(1 - \sum_{t \in T} x_{v,i,j,t,m}\right) + \left(1 - br_{v,i,m}\right) \qquad \forall v \in V; i, j \in N; i \neq j; m \in M \tag{18}$$

If a full break or a second part of a break is finally taken at node i, then the conserving binary decision variable $FIF_{v,j,m}$ for a possible first part of a break is initialized with zero again at the next node j. This restriction is irrelevant for non-consecutive nodes (i.e. if $x_{v,i,j,t,m}$ is set false).

$$FIF_{v,j,m} \leq \left(1 - \sum_{t \in T} x_{v,i,j,t,m}\right) + \left(1 - dr_{v,i,m}\right) \qquad \forall v \in V; i, j \in N; i \neq j; m \in M \tag{19}$$

Similar to the previous constraint, the conserving binary decision variable $FIF_{v,j,m}$ for a possible first part of a break is initialized with zero again at the next node j, if a full daily rest period or a second part of a daily rest period is taken at node i. Again, non-consecutive nodes (i.e. if $x_{v,i,j,t,m}$ is set false) are not affected here.

$$\begin{aligned} & THR_{v,i,m} + thrhour_{v,i,m} + BIG \\ & * \left(1 - \sum_{t \in T} x_{v,i,j,t,m}\right) \geq THR_{v,j,m} \\ & \forall v \in V; i, j \in N; i \neq j; m \in M \end{aligned} \tag{20}$$

This constraint, arranging for the conservation of a first part of a daily rest period, is based on the exact same underlying principle as described in constraint (17).

$$THR_{v,j,m} \leq \left(1 - \sum_{t \in T} x_{v,i,j,t,m}\right) + \left(1 - dr_{v,i,m}\right) \qquad \forall v \in V; i, j \in N; i \neq j; m \in M \tag{21}$$

If a full daily rest period or a second part of such a pause is finally taken at node i, then the conserving binary decision variable $THR_{v,j,m}$ for a possible first part of a daily rest period is initialized with zero again at the next node j. Here as well, the restriction is irrelevant for non-consecutive nodes (i.e. if $x_{v,i,j,t,m}$ is set false).

$$\begin{aligned} min1_m \leq dbr_{v,i,m} + BIG * \left(1 - br_{v,i,m}\right) \\ + redbr_m * FIF_{v,i,m} \\ \forall v \in V; i \in N; m \in M \end{aligned} \tag{22}$$

This inequality ensures that a full compulsory break, or a second part of it, fulfills the minimum temporal requirements according to European law. If there is no partial break since the last daily rest period when approaching node i, the full mandatory break time is assigned to the integer decision variable $dbr_{v,i,m}$ at node i. However, in case such a first break part is taken at some location before, this information is conserved by $FIF_{v,i,m}$ and exploited here to reduce the minimum full break time $min1_m$ by a factor $redbr_m$ to receive the second part's duration.

$$\begin{aligned} min2_m \leq ddr_{v,i,m} + BIG * \left(1 - dr_{v,i,m}\right) \\ + reddr_m * THR_{v,i,m} \\ \forall v \in V; i \in N; m \in M \end{aligned} \tag{23}$$

Similar to the previous constraint, this restriction enforces the minimum temporal requirements for a full or second part of a mandatory daily rest period.

$$fifmin_{v,i,m} \leq 1 - br_{v,i,m} \qquad \forall v \in V; i \in N; m \in M \tag{24}$$

A first part of a break must not be taken at the same location as a full or second part of a break.

$$fifmin_{v,i,m} \leq 1 - dr_{v,i,m} \qquad \forall v \in V; i \in N; m \in M \tag{25}$$

Similarly, a first part of a break must not be taken at the same location as a full or second part of a daily rest period.

$$thrhour_{v,i,m} \leq 1 - br_{v,i,m} \qquad \forall v \in V; i \in N; m \in M \tag{26}$$

A first part of a daily rest period must not be taken at the same location as a full or second part of a break.

$$thrhour_{v,i,m} \leq 1 - dr_{v,i,m} \qquad \forall v \in V; i \in N; m \in M \tag{27}$$

Similarly, a first part of a daily rest period must not be taken at the same location as a full or second part of a daily rest period.

$$thrhour_{v,i,m} \leq 1 - fifmin_{v,i,m} \qquad \forall v \in V; i \in N; m \in M \tag{28}$$

Moreover, a first part of a daily rest period must not be taken at the same location as a first part of a break.

$$brClock_{v,ori_v,m}, drClock_{v,ori_v,m} = 0 \qquad \forall v \in V; m \in M \tag{29}$$

As a start condition at the origin, the integer clock variables to determine the timing of a truck's mandatory breaks and daily rest periods are initialized with zero.

$$br_{v,ori_v,m}, br_{v,des_v,m}, dr_{v,ori_v,m}, dr_{v,des_v,m} = 0 \quad \forall v \in V; m \in M \tag{30}$$

Similarly, the binary decision variables relating to full breaks and daily rest periods, or to their respective second parts, are set to zero at an individual truck's origin and destination because no pauses are considered here anyway.

$$FIF_{v,ori_v,m}, THR_{v,ori_v,m} = 0 \quad \forall v \in V; m \in M \tag{31}$$

The binary auxiliary variables to conserve information about previously taken first parts of breaks or daily rest periods are initialized with zero at the origin.

$$fifmin_{v,ori_v,m}, fifmin_{v,des_v,m}, thrhour_{v,ori_v,m}, thrhour_{v,des_v,m} = 0 \quad \forall v \in V; m \in M \tag{32}$$

Similarly, the binary decision variables relating to first parts of breaks or daily rest periods are set to zero at an individual truck's origin and destination because no pauses are considered here anyway.

$$FIF_{v,i,2}, fifmin_{v,i,2}, THR_{v,i,2}, thrhour_{v,i,2} = 0 \quad \forall v \in V; i \in N \tag{33}$$

As optional splitting rules are neither useful nor provided for multi-manned trucks by European lawmakers, all associated decision variables are generally set to zero. While constraints (34) – (36) ensure the binary condition for the listed decision variables, restrictions (37) and (38) indicate the non-negative, integer domains of definition for the remaining decision variables.

$$x_{v,i,j,t,m}, \alpha_{v,i,j,t,m} \in \{0,1\} \quad \forall v \in V; i,j \in N; i \neq j; t \in T; m \in M \tag{34}$$

$$pl_{v,u,i,j,t} \in \{0,1\} \quad \forall v,u \in V; v \neq u; i,j \in N; i \neq j; t \in T \tag{35}$$

$$br_{v,i,m}, dr_{v,i,m}, fifmin_{v,i,m}, thrhour_{v,i,m}, FIF_{v,i,m}, THR_{v,i,m} \in \{0,1\} \quad \forall v \in V; i \in N; m \in M \tag{36}$$

$$a_{v,i,m}, w_{v,i,m}, dbr_{v,i,m}, ddr_{v,i,m}, brClock_{v,i,m}, drClock_{v,i,m} \in \mathbb{Z}_+ \quad \forall v \in V; i \in N; m \in M \tag{37}$$

$$late_{v,m} \in \mathbb{Z}_+ \quad \forall v \in V, m \in M \tag{38}$$

4.2. Hierarchical planning-based matheuristics

Our review of literature and research in chapter 3 has already shown that even the basic PP is already computationally intractable due to its NP-hardness – be it in terms of problem sizes or, first and foremost, from a computational runtime perspective. Therefore, heuristics have been proposed by different publications. We also address this important aspect of computational complexity by introducing two approximate approaches based on hierarchical planning. After setting out the basic principles behind our problem-specific matheurstic solution approaches for the exact EU-TPP, we present the mathematical realization of the Shortest Path Heuristic (SPH) and the Platoon Routing Heuristic (PRH) and compare their characteristics against those of the exact model. Please note that both matheuristics in their compact form are provided in Appendix C and D respectively.

4.2.1. Conceptual framework

The EU-TPP in its basic form contains three essential decision components: routing (along with pause location and manning decisions), scheduling and resultant platooning decisions. On the one hand, cost-efficient routes have to be found, considering the trade-off between potentially longer detours, (additional) personnel costs and benefits from platooning. On the other hand, tours must be scheduled accordingly while taking earliest departure and latest arrival times, optional waiting times as well as times for mandatory breaks and daily rest periods after a maximum accumulated amount of driving time into account. Putting all of these per se complex decisions together in one model to find an optimal trip plan based on platooning inevitably leads to a drastically increasing complexity. However, this combinatorial framework seems predestinated to be subdivided into different hierarchical problem levels which can be solved in a consecutive manner. Our idea is thus to refer back to the three basic decision components to make use of their individual capabilities by applying a hierarchical planning-based approach.

This kind of approximation method has already been proposed by Minner (2017a) as a field for further research with regard to platooning. Stiglic et al. (2015) also use the hierarchy concept during their investigations about the benefits of meeting points in ridesharing systems. Herein, they solve the single driver – multiple riders rideshare matching problem by maximizing the amount of passenger matches first, before maximizing the total mileage savings in the next step. A comparison with two slightly adapted objective hierarchies is performed afterwards to evaluate their particular benefits. Such a stepwise approach also seems appropriate for a similar setting like ours, where trucks have to be matched by schedule and possible route adaptations to form a platoon, ultimately aiming at the realization of fuel savings from platooning. Considering our three-part decision process along with the stimulus from Stiglic et al. (2015), we are interested in exploiting our existing mathematical formulation of the exact EU-TPP in the previous section as much as possible to maintain its basic characteristics for the solution process.

For this purpose, we transfer these thoughts into matheuristics, i.e. heuristics which are primarily based on the exploitation of an existing mathematical model's features. Especially complex combinatorial optimization problems like the VRP are typical use cases. Although exact algorithms are often combined with commonly known metaheuristic concepts in such a type of heuristic, the structural decomposition of exact methods is another important strategy in this field. The idea lies basically in "reducing the model sizes through decomposition approaches [. . .] to tackle smaller and simpler (sub-)problems, in an exact manner [. . .] on the basis of an implicit hierarchy among the decision levels involved, or of a natural separation into partial problems" (Labadie et al., 2016, pp. 109-147). This leads to a complementary combination of the exact method's optimizing capabilities and a more efficient heuristic solution process. Hence, we decide to apply hierarchical optimization based on matheuristics. The basic structure of our two approximation approaches is illustrated in figure 7 below.

Separating the routing, manning and pause location decisions from the scheduling and platoon coordination parts of the exact EU-TPP is expected to make both problems per se easier to be solved efficiently.

4.2.2. The Shortest Path Heuristic (SPH) – stage 1

Our first approach – the Shortest Path Heuristic (SPH) – is based on the assumption that truck drivers will anyway take the shortest path on their way from origin to destination in most of the cases. Not only because "anecdotal surveys of HDV drivers suggest that few are willing to spend additional time behind the wheel in order to save fuel" (Larson et al., 2013), but also due to the aforementioned cost tradeoff, longer detours in favor of platooning would rarely occur. Even more in case of double manning when two wage rates instead of one need to be considered, the shortest path would usually be the first choice.

Stage 1 of this hierarchical heuristic is specifically dedicated to the determination of the shortest path for each truck while simultaneously deciding upon manning and the location for compulsory breaks and daily rest periods. However, the exact scheduling and determination of designated time indices is not done here yet. Since we do not know anything about timing and scheduled platooning opportunities yet, splitting rules as well as the potential task-relieving effect of trailing are ignored here. Let us introduce a new auxiliary variable $y_{v,i,j,m}$ which fulfills the same function as the binary variable $x_{v,i,j,t,m}$ before, i.e. to assign edge traversals, but without a temporal index. The idea is now to use the output of the decision variables $y_{v,i,j,m}$, $dbr_{v,i,m}$ and $ddr_{v,i,m}$ as an input for the optimization model which follows in stage 2 of our matheuristic approach. That next optimization step will then perform the final scheduling and platoon coordination by assigning explicit time indices at given locations based on these inputs (see subsection 4.2.4).

Due to this stepwise procedure, our first objective (39) is just to minimize the accumulated, financially charged time spent on the road and the duration of mandatory pauses first. For a mere single manning formulation, only minimizing these accumulated time components would be sufficient as every time step is charged equally in such a setting. The separate consideration of fuel or penalty cost is not necessarily required to get the right input parameters for the second step's model.

Objective

$$\text{Minimize} Z = \sum_{v\in V}\sum_{i\in N}\sum_{m\in M} p_m \\ *(dbr_{v,i,m} + ddr_{v,i,m} + \sum_{j\in N\setminus i} d_{i,j} * y_{v,i,j,m}) \tag{39}$$

All of the following constraints are similar to those presented in the basic EU-TPP and thus just slightly modified. To this end, we will keep their explanation short.

subject to

$$\sum_{i\in N\setminus\{des_v\}} y_{v,i,j,m} = \sum_{i\in N\setminus\{ori_v\}} y_{v,j,i,m} \\ \forall v\in V; j\in N\setminus\{ori_v, des_v\}; i\neq j; m\in M \tag{40}$$

$$\sum_{j\in N\setminus\{ori_v\}}\sum_{m\in M} y_{v,ori_v,j,m} = 1 \quad \forall v\in V \tag{41}$$

$$\sum_{i\in N\setminus\{des_v\}}\sum_{m\in M} y_{v,i,des_v,m} = 1 \quad \forall v\in V \tag{42}$$

The first three constraints are necessary for node balancing. Being manned with m drivers, trucks start from their origin, enter and leave (if any) intermediate nodes to conserve the vehicle flow and must reach their destinations respectively.

$$brClock_{v,i,m} + d_{i,j} * y_{v,i,j,m} - \\ BIG * (1 - y_{v,i,j,m}) - BIG * br_{v,j,m} - \\ BIG * dr_{v,j,m} \leq brClock_{v,j,m} \\ \forall v\in V; i,j\in N; i\neq j; m\in M \tag{43}$$

$$drClock_{v,i,m} + d_{i,j} * y_{v,i,j,m} - \\ BIG * (1 - y_{v,i,j,m}) - BIG * dr_{v,j,m} \leq drClock_{v,j,m} \\ \forall v\in V; i,j\in N; i\neq j; m\in M \tag{44}$$

$$max1_m - brClock_{v,i,m} - d_{i,j} * y_{v,i,j,m} \geq 0 \\ \forall v\in V; i,j\in N; i\neq j; m\in M \tag{45}$$

$$max2_m - drClock_{v,i,m} - d_{i,j} * y_{v,i,j,m} \geq 0 \\ \forall v\in V; i,j\in N; i\neq j; m\in M \tag{46}$$

In order to enforce that mandatory breaks or daily rest periods are taken before the particular driving time limit is

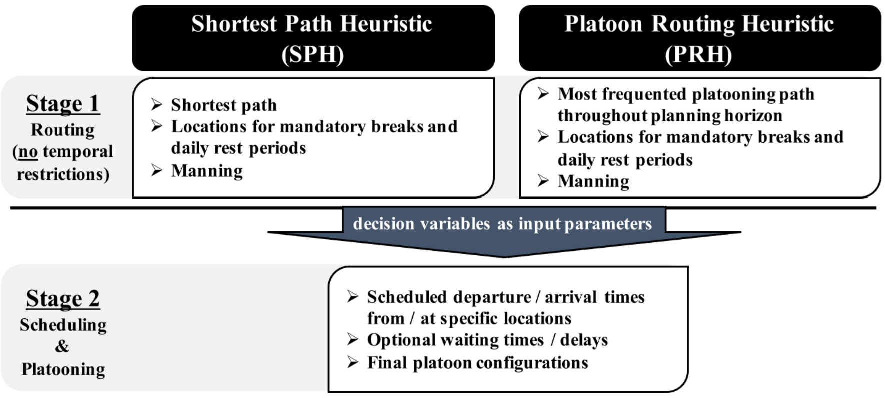

Figure 7: Basic structure of hierarchical planning-based matheuristics

exceeded, conditions (45) and (46) monitor the truck driver's status which is calculated in restrictions (43) and (44).

$$min1_m \leq dbr_{v,i,m} + BIG * \left(1 - br_{v,i,m}\right) \quad \forall v \in V; i \in N; m \in M \tag{47}$$

$$min2_m \leq ddr_{v,i,m} + BIG * \left(1 - dr_{v,i,m}\right) \quad \forall v \in V; i \in N; m \in M \tag{48}$$

In compliance with Regulation (EC) No 561/2006, the previous two constraints ensure that mandatory breaks or daily rests have the required minimum duration. Finally, the corresponding domains of definition are outlined by restrictions (49) – (51) whereas the necessary start conditions (29) and (30) for the clock and binary variables from the basic EU-TPP model are appended.

$$y_{v,i,j,m} \in \{0,1\} \quad \forall v \in V; i,j \in N; i \neq j; m \in M \tag{49}$$

$$br_{v,i,m}, dr_{v,i,m} \in \{0,1\} \quad \forall v \in V; i \in N; m \in M \tag{50}$$

$$dbr_{v,i,m}, ddr_{v,i,m}, brClock_{v,i,m}, drClock_{v,i,m} \in \mathbb{Z}_+ \quad \forall v \in V; i \in N; m \in M \tag{51}$$

Additionally: (29), (30)

4.2.3. The Platoon Routing Heuristic (PRH) – stage 1

Our second approach – the Platoon Routing Heuristic (PRH) – assumes that trucks choose the most frequented route throughout the planning horizon on their way from origin to destination. In other words: the first level of the PRH involves theoretically appearing platoons in its optimization process by still ignoring their general feasibility in terms of time. This may seem less intuitive than the previous strategy based on shortest paths. But on the one hand, the generated set of paths may also include a lot of these shortest routes anyway as detours for the sake of platooning must at first be financially justified. And on the other hand, it leaves an open space for slightly longer or comparably long routes, which could actually exhibit more platooning opportunities in the end: the so-called 'platoon routes'.

Therefore, stage 1 shares exactly the same modeling features as the SPH. However, unlike the previous heuristic, the PRH additionally takes the known, but temporally unrestricted platooning constraints of the basic EU-TPP into account. Since we do not know the final platoon configurations yet, the issue of a conceivable task relief when trailing is also disregarded here – just like splitting rules. The decision variables $y_{v,i,j,m}$, $dbr_{v,i,m}$ and $ddr_{v,i,m}$ are used as input parameters for stage 2 as well, which both approaches have in common. Consequently, the concrete schedules and platooning decisions are only made in this next stage (see subsection 4.2.4).

In contrast to the SPH, the first objective function (52) of the PRH minimizes the total fuel cost next to truck driver expenses as we need to take potential reductions in fuel consumption due to hypothetical platooning into account.

$$\text{Minimize } Z = \sum_{v\in V}\sum_{i\in N}\sum_{j\in N\setminus i}\sum_{m\in M} c * f_v * d_{i,j} * \left(\alpha_{v,i,j,m} + \eta * \left(y_{v,i,j,m} - \alpha_{v,i,j,m}\right)\right) + \sum_{v\in V}\sum_{i\in N}\sum_{m\in M} p_m * (dbr_{v,i,m} + ddr_{v,i,m} + \sum_{j\in N\setminus i} d_{i,j} * y_{v,i,j,m}) \tag{52}$$

Since we can exploit the full range of restrictions from the SPH's first stage – which are referred to below – we only introduce an adapted set of constraints at this point which we know in a temporally restricted form from the basic EU-TPP.

$$2 * pl_{v,u,i,j} - (\sum_{m\in M} y_{v,i,j,m} + \sum_{n\in M} y_{u,i,j,n}) \leq 0 \quad \forall v,u \in V; u < v; i,j \in N; i \neq j \tag{53}$$

$$\sum_{m\in M}\alpha_{v,i,j,m}+\sum_{u=1}^{v-1}pl_{v,u,i,j}\geq\sum_{m\in M}y_{v,i,j,m} \quad \forall v\in V;i,j\in N;i\neq j \tag{54}$$

$$\alpha_{v,i,j,m}\leq y_{v,i,j,m} \quad \forall v\in V;i,j\in N;i\neq j;m\in M \tag{55}$$

$$\sum_{m\in M}\alpha_{v,i,j,m}\geq pl_{u,v,i,j} \quad \forall v,u\in V;v<u;i,j\in N;i\neq j \tag{56}$$

The platooning-based restrictions (53) – (56) determine which trucks theoretically platoon with each other and impose the respective roles of a PF or PL to each truck, based on the convention that those vehicles with lower indices are leading or individually driving ones.

The variable domains (57) and (58) along with the appended constraints from the SPH round off stage 1 of the PRH.

$$\alpha_{v,i,j,m}\in\{0,1\} \quad \forall v\in V;i,j\in N;i\neq j;m\in M \tag{57}$$

$$pl_{v,u,i,j}\in\{0,1\} \quad \forall v,u\in V;v\neq u;i,j\in N;i\neq \tag{58}$$

Additionally: $(29),(30),(40)-(51)$

4.2.4. Shortest Path and Platoon Routing Heuristic – stage 2

After performing the routing decisions with an accompanying determination of the locations for mandatory idle times in stage 1 of our two matheuristic approaches, the final scheduling and platooning decisions are now made on the consecutive level based on the three new parameters $y_{v,i,j,m}$, $dbr_{v,i,m}$ and $ddr_{v,i,m}$. This optimization problem resembles our basic version of the exact EU-TPP model without all those restrictions relating to mandatory driving times, breaks and daily rests as these have already been scheduled in the first stage of the hierarchy. Furthermore, three slight adaptations are required, as can be seen below.

Objective

$$\text{Minimize} Z=(1) \tag{59}$$

subject to

$$\sum_{t\in T}x_{v,i,j,t,m}=y_{v,i,j,m} \quad \forall v\in V;i,j\in N;i\neq j;m\in M \tag{60}$$

$$a_{v,i,m}+dbr_{v,i,m}+ddr_{v,i,m}+w_{v,i,m}\leq \sum_{j\in N\setminus\{ori_v\}}\sum_{t\in T}x_{v,i,j,t,m}*t \tag{61}$$
$$\forall v\in V;i\in N\setminus\{ori_v,des_v\};i\neq j;m\in M$$

$$a_{v,i,m},w_{v,i,m}\in\mathbb{Z}_+ \quad \forall v\in V;i\in N;m\in M \tag{62}$$

Additionally: $(2)-(7),(9)-(12),(34),(35),(38)$

Firstly, we need to assign the value of the introduced auxiliary variable $y_{v,i,j,m}$, which is now a parameter, to the time-indexed binary decision variable $x_{v,i,j,t,m}$ in constraint (60). This serves to indicate when the m-manned truck v traverses edge (i,j) and sets the respective node-leaving time t. Secondly, the departure time condition from an intermediate location in restriction (61) must be reduced by the elements regarding break and daily rest period splitting. And thirdly, condition (62) defines the arrival time $a_{v,i,m}$ and waiting time $w_{v,i,m}$ at node i in a non-negative integer value range. As appended, all other constraints of the conventional EU-TPP model except from those pause scheduling ones remain the same.

4.2.5. Limitations

Despite the expected higher computational efficiency of our hierarchical optimization-based matheuristics compared to the exact EU-TPP model, such approaches are usually associated with simplifying assumptions and therefore a lower average solution quality in turn. Hence, we discuss some of their limitations next, before we actually investigate their computational efficiency in more detail later on.

As the SPH is based on a truck taking the shortest possible route between its origin-destination pair and thus causes the minimum distance- and time-dependent travel cost on its own, it represents common practice in today's transport sector anyway. Against that background, a retrospective integration of platooning decisions seems appropriate for a real-world application, even if this means less chances to trail behind another truck than with taking a different path. The PRH by contrast, rather aims at maximizing the potential convoy opportunities, but could possibly create misleading decisions as well. This becomes particularly evident when many trucks throughout the planning horizon merge to platoons on a specific detour indeed, but their respective time windows turn out to exhibit no overlap in stage 2. As a result, trucks would travel longer distances in expectation of reduced fuel consumptions without actually being able to realize them. In the special case of evenly long routes, the SPH could favor the one with less chances to platoon while the PRH would hold the minimum distance advantage as well. So the ideal case would be that most platooning options arise on a unique shortest path. Ultimately, there can be a trade-off between the shortest path and the probability to platoon when comparing the two matheuristics from a route perspective.

Moreover, the break and rest locations are predetermined and fixed by stage 1. This can have a restricting effect for the formation and dissolution of platoons. For example, taking a mandatory break too early or too late could result in a missed platoon opportunity or mean that the platooning partners cannot travel as long distances together as they actually could when performing a joint optimization of all objectives (i.e. routing, scheduling and platooning). Since no splitting rules are applied in the heuristics due to the lack of temporal schedule information in the first stage, there is also an inherent lack of flexibility to set pauses accordingly for platooning purposes.

Theoretically possible task reliefs when driving as a follower in a convoy are still ignored because pause locations are planned regardless of temporally feasible platooning options in our two-step approach. Nevertheless, we prospectively want to give a glimpse into how such an effect could also be integrated in a modified version of this type of strategy. After determining preliminary platoon configurations in stage 2, this information could be reported to an additional stage 3 which resembles the EU-TPP in its original form without splitting rules. To this end, $x_{v,i,j,m}$ as well as the platooning-related decision variables $\alpha_{v,i,j,m}$ and $pl_{v,u,i,j}$ are used as input parameters without their temporal dimensions. Now there are two options: Either the final scheduling is done here with new, possibly less pauses due to a task relief. Or breaks and rests can be recalculated and handed over to stage 2 again, where the precise scheduling and platoon coordination starts anew. This refinement procedure can be repeated until a certain stopping criterion is met. However, both alternatives would presumably raise computational efforts again.

Manning is another aspect which is related to the issue of task relief. One instead of two drivers could sometimes be sufficient if being a PF gets less charged with a task relief than being a PL. Thus, a less favorable manning decision than within a joint optimization approach could actually be the outcome of our heuristics.

As can be seen, both approximate strategies have their downsides. Therefore, we need to put these drawbacks in relation to their actual benefits later on.

4.3. Benchmark models

After introducing an ILP formulation for the exact EU-TPP and two hierarchical planning-based matheuristics, we need to define the necessary benchmark models in the next step in order to provide well-founded answers for the given research questions in this thesis. Next to a standard transport planning problem for the EU, we shortly present a basic platooning model without the consideration of mandatory breaks and daily rest periods.

4.3.1. Standard planning model in the EU

Fleet managers nowadays already have to meet the requirements of Regulation (EC) No 561/2006 when planning their tours, but still without the need to take advantageous aspects of platooning into account. Minor adaptations would thus be sufficient to reduce the EU-TPP to the standard transport planning problem in a European legal framework which is usually based on shortest paths. However, we do not have to consider temporal constraints or pause splitting rules for our purposes which would normally represent important factors for efficient truck fleet management. Since we only need the necessary financial benchmarks in order to evaluate and prove the implied savings potentials from platooning, we rather resort to a slightly modified version of stage 1 of our SPH approach in consequence. While all its constraints can be utilized without exception, we just replace $y_{v,i,j,m}$ by $x_{v,i,j,m}$ again as the binary decision variable for edge traversals. Since we are especially interested in acquiring the respective fuel-related cost components for our investigations based on platooning, objective function (63) below minimizes the sum of fuel and personnel cost.

$$\begin{aligned}\text{Minimize} Z = &\sum_{v\in V}\sum_{i\in N}\sum_{j\in N\setminus i}\sum_{m\in M} c * f_v * d_{i,j} * x_{v,i,j,m}\\ &+\sum_{v\in V}\sum_{i\in N}\sum_{m\in M} p_m * (dbr_{v,i,m} + ddr_{v,i,m}\\ &+\sum_{j\in N\setminus i} d_{i,j} * x_{v,i,j,m})\end{aligned} \tag{63}$$

subject to $(29),(30),(40)-(51)$

Please note that the entire model in its compact form is provided in Appendix E.

4.3.2. Basic platooning model without driving time restrictions

Unlike all scientific contributions in the field of platooning so far, we incorporate essential European transport law within our investigations – this is crucial for fleet managers in real-world applications. The following basic platooning model will help us provide some insights on the influence of compulsory breaks and daily rest periods on the coordination of platoons later on. While the basic EU-TPP model and the mere platooning approach share the same objective function (64), all constraints, parameters or decision variables relating to Regulation (EC) No 561/2006 are removed in the latter one. That is why optional waiting times are the only existing type of time lags left on a trip after an arrival at an intermediate node, as can be seen in constraint (65).

Objective

$$\text{Minimize } Z = (1) \tag{64}$$

subject to

$$a_{v,i,m} + w_{v,i,m} \leq \sum_{j\in N\setminus\{ori_v\}}\sum_{t\in T} x_{v,i,j,t,m} * t \quad \forall v\in V; i\in N\setminus\{ori_v, des_v\}; i\neq j; m\in M \tag{65}$$

Additionally: $(2)-(7),(9)-(12),(34),(35),(38),(62)$

Please note that the entire model in its compact form is provided in Appendix F.

4.4. Efficient implementation

We have already provided a matheuristic approach which is specifically designed for the exact EU-TPP to address the issue of computational complexity. In order to promote the efficient implementation into an appropriate optimization software even further, we subsequently focus on two additional efficiency-raising methods.

4.4.1. Pruning-based auxiliary constraint

Naïvely implementing the EU-TPP and the related platooning-based models above would result in longer processing times than it would be the case with some kind of pruning with regard to the generation of decision variables. To this end, we want to extend the basic systematic approach to increase the computational efficiency which is utilized by Nourmohammadzadeh and Hartmann (2016), Larson et al. (2016) and Sokolov et al. (2017).

Here, the binary values of the decision variable $x_{v,i,j,t,m}$ (denoted differently in these scientific publications) to determine actual edge traversals are only generated when these seem realistic and reasonable in a platooning context at all. Their approach is based on the assumption that truck drivers will usually not deviate more than a certain threshold distance from their shortest path in order to enjoy the fuel-saving benefits from exploiting the slipstream effect. As an upper bound for such a route deviation between a truck's individual origin and destination, $1/\eta$ times its shortest path is practically feasible and realistic according to them. Hence, let us introduce a new parameter $short_v$ for the shortest path of vehicle v on its assigned origin-destination route. Transferred to our exact EU-TPP model, their reflections would result in the following auxiliary constraint:

$$\sum_{i\in N}\sum_{j\in N\setminus i}\sum_{t\in T} x_{v,i,j,t,m} * d_{i,j} \leq short_v * \frac{1}{\eta} \qquad \forall v \in V; m \in M \tag{66}$$

This additional condition ensures that any extra kilometers or time steps of driving must at best be balanced with the maximally possible fuel savings of driving in a platoon on that specific detour. However, they do not account for extra personnel costs which additionally occur on such longer routes as a side effect. Since we take this important transport cost component into consideration within our approach, we intend to further narrow down the number of feasible edge traversals for the optimization software. The basic principle is illustrated in figure 8.

Mathematically, we can then include these new upper bound considerations for a maximum route deviation as follows:

$$\sum_{i\in N}\sum_{j\in N\setminus i}\sum_{t\in T} x_{v,i,j,t,m} * d_{i,j} \leq Short_v * \frac{c * f_v + p_m}{c * f_v * \eta + p_m} \qquad \forall v \in V; m \in M \tag{67}$$

This extended constraint justifies a detour only if the sum of the maximally reduced fuel cost due to platooning and additional wages on this longer route is smaller than on a truck's shortest path without platooning options. Hence, we aim to use this condition within our later experiments to reduce the computational complexity of the EU-TPP, the PRH (stage 1) and the mere platooning model where route decisions are made jointly (at least hypothetically in case of the PRH) with those for platooning. To this end, its efficiency-raising character needs to be validated first before actually applying it in our quantitative experiments later.

4.4.2. Adequate choice of Big-M

The Big-M parameters used within our break and daily rest period computations, as for example in constraint (13), do not need to have uniform values. Quite the contrary – uniform, unsuitable values of BIG for different problem instances to be solved can actually increase the computational efforts. For our later implementation into the optimization software Xpress by FICO, we can exploit the so-called 'indicator constraints' to this end. These software-specific types of restrictions make the extra definition of sufficiently large, minimum numbers for Big-M parameters redundant. To do so, Xpress associates a certain binary variable with an explicit linear constraint and can thus handle such constraints more efficiently than those with manually chosen values of BIG. Nevertheless, we still have to define a minimum value for BIG because the aforementioned exemplary constraint includes three such parameters. And indicator constraints, in turn, can only establish one association at a time. Consequently, we will resort to indicator constraints to some extent along with a manual choice of the Big-M parameter.

Already anticipating our later experiments, we decide to set its minimum value carefully to 72 in case of multi manning and to 36 in case of single manning (corresponds to 18 h / 9 h due to the time steps defined on a 15 min interval). The reason for this can be found when having a closer look at restriction (14) which prevents $drClock_{v,i,m}$ from becoming larger than these maximum accumulated daily driving time values. In order to set the clock variable false when a daily rest period is taken or non-consecutive nodes are affected (i.e. we want to reset the truck driver's status or leave it at zero anyway), BIG must excel its current value to satisfy constraint (14). This is finally ensured by using the daily driving time limit as a reference value. Restriction (13) is satisfied with this choice of BIG as well.

After presenting our modeling approaches along with some insights into raising the overall computational efficiency, we will now make some required preparations for our extensive numerical experiments, including a prior validation of the exact EU-TPP model and the two matheuristics.

5. Basic Preparations

The previous chapters provided a solid foundation to base our numerical investigations upon. In order to be able to actually start with our major experiments in the next chapter though, we still need to make some arrangements in advance, including the establishment of a suitable experimental setup. A validation section of our EU-TPP-based mathematical model approaches then bridges to the actual quantitative investigations by proving their specific features.

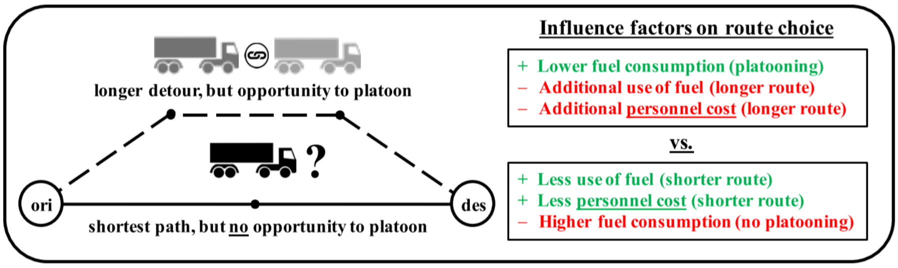

Figure 8: Concept behind pruning-based auxiliary constraint

5.1. Experimental setup

The following subsections will first present the underlying highway network graph with further essential settings, before the tailored assessment procedure for our numerical experiments is described in more detail. Necessary performance indicators are defined in this context as well.

The execution of all our computational experiments is done on a computer with an Intel® Core™i5-4210M CPU (2.60 GHz) and 16 GB of RAM. We use Xpress by FICO as optimization software to solve our problem instances.

5.1.1. Road network graph and basic settings

Since this thesis focuses on platooning under consideration of mandatory driving time regulations in the EU, we decided to use major transportation links on the European highway network for our research. To this end, 22 important cities with a direct motorway access in Germany, Austria and Italy are chosen to serve as origins, destinations and intermediate nodes for required breaks, daily rests or optional waiting times on specific routes. The red connections in figure 9 represent the respective distances between the locations in terms of their shortest paths. These are derived from Google Maps as approximate instead of exact distances to create links of equal length on the undirected graph. We choose equally long edges as multiples of our 15 min time steps for one special reason: consistency. On the one hand, first test instances of the exact EU-TPP implemented into Xpress have shown that only a limited number of nodes and related arcs can be generated to prevent the computer from crashing while considering a relevant amount of trucks in the network. On the other hand, though, the single rules of Regulation (EC) No 561/2006 which are applied in this thesis necessitate a certain amount of nodes to be able to take breaks or daily rests at all. As a consequence, this trade-off forces us to balance the distances between locations in order to represent accumulated driving times as multiples of these node connections. So each arc is assumed to have a length of 6 time steps. Otherwise, in case of unequal distances, we would risk to schedule breaks or rest periods just because an edge traversal is not possible anymore, even if there is still some driving time left before a compulsory pause is actually required. Such an aspect would not matter if an auxiliary node could be inserted after every step of 15 min.

Additionally, we assume the trucks' highway velocity to be constant at 80 km/h – a speed where platooning can bring up its entire fuel saving potential. To this end and to show the impact of platooning even better than in many other, rather modest studies on convoy coordination, we calculate with a fixed fuel reduction rate of 15% instead of 10% when driving in the slipstream. According to our literature findings, this is still a quite realistic value, even more when further technological advances allow smaller inter-vehicle distances than today (see Tsugawa, 2013).

While the cost for Diesel and AdBlue are given by 1.20 € per liter, we base our calculations upon an equal fuel consumption of 6 l per time step of 20 km. A single truck driver's hourly wages are fixed at 15.00 € . We apply a 50% 'discount' on the actual driving time for followers to anticipate legal changes in the EU, whereas a task-relieving factor of 0% is set as default. Finally, the penalty cost rate per delayed time unit is set extremely high to avoid later arrivals at first.

After using all these default input parameters for our comprehensive numerical experiments, some of them will be varied during a qualitative sensitivity analysis later on to further investigate the impact of certain influence factors on platoon coordination. Our experiments are conducted based on a planning horizon of 120 time steps (i.e. 30 h) and are thus well in line with all legal driving time restrictions in the EU. Given the fact that trips are often planned on a daily basis anyway and a longer horizon would also increase computational complexity even further, such a time frame also seems reasonable from a practical point of view.

5.1.2. Assessment procedure

Based on the network data provided in the previous subsection, we create four different problem sizes with 3, 6, 9 and 12 trucks respectively to get some insights into the importance of a certain network saturation level for platooning. More HDVs will presumably increase the chances to find appropriate platooning partners if drivers have to comply with mandatory breaks and daily rest periods according to EU law. Both their origin and destination nodes are randomly selected from the set of 22 locations in order to show the impact of centrally coordinating trucks from different nodes. Since we also intend to contrast these different-start instances with cases of centrally coordinated platoons from a single hub, we create instances where all trucks share the same randomly chosen origin in a same-start setting as well. It is expected that coordinating HDVs from a single location will result in

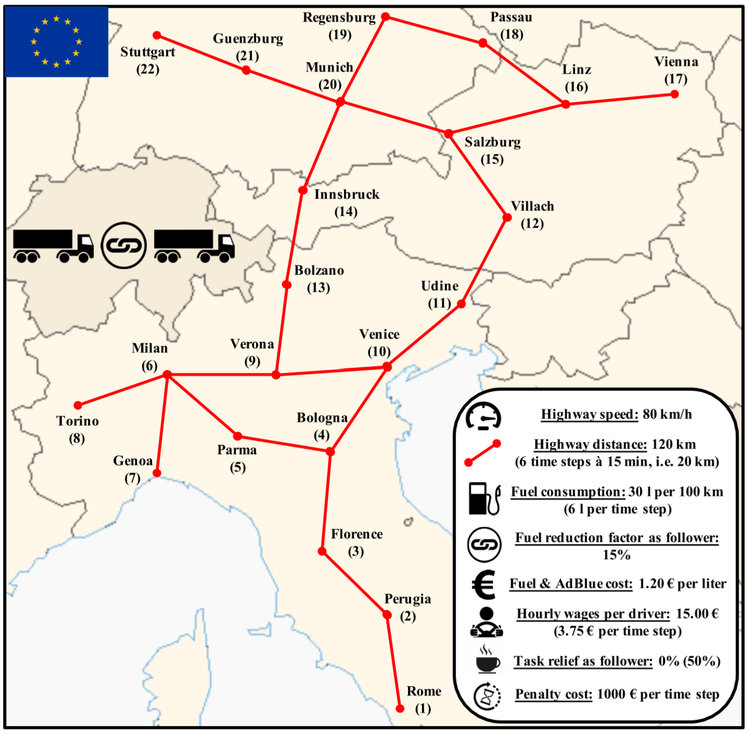

Figure 9: European highway network graph and basic settings

higher platooning-related fuel cost savings than the coordination of widely dispersed vehicles in the highway network.

As we want to additionally demonstrate that flexibility is an important requirement for trucks to platoon under strict driving time regulations, two different types of time windows are compared. The first type allows each truck to cover its respective route distance at any time between time steps 0 and 120, i.e. the full planning horizon can be exploited at maximum flexibility. The second more restricted time window is generated by randomly choosing its center on a uniform distribution between (0+shortest path/2) and (120-shortest path/2), while also allowing a small symmetric buffer of maximally 20 time steps in addition to its shortest path duration. In other words: the earliest possible departure and latest possible arrival times can be shifted by 10 time steps at most in each direction respectively. Since strictly abiding by extremely narrow time windows without any buffer would most probably result in platooning HDVs just by accident, we decided to add at least a little temporal markup to enable some smart scheduling. We call the combination of a different- / same-start problem with one of the two time window frames a type of coordination problem or type of problem instances.

The major focus of this thesis is to provide valid statements about the financial savings potentials from platooning while simultaneously complying with the mandatory driving time restrictions in Regulation (EC) No 561/2006. To this end, we benchmark our exact EU-TPP model and the two approximate matheuristics against the easy-to-solve present-day standard without platooning options in the EU as presented in subsection 4.3.1.

Contrasting the basic EU-TPP with the mere platooning model from subsection 4.3.2 will help us assess the impact of required breaks and daily rest periods on cost-efficient platoon coordination. To this end, we use the same earliest possible departure and latest possible arrival times in the restricted cases for both models to be compared. Leaving strict EU law out of consideration is assumed to provide an increased flexibility level as the planning horizon does not have to include pause times anymore. We expect that substantially less platoons can be formed in the presence of strict driving time regulations – especially when narrow time windows allow for less flexibility anyway.

Moreover, the implications of a possible 'discount' on the actually charged driving time when trailing as a follower in a platoon are analyzed by comparing the conventional EU-TPP with the EU-TPP under a hypothetical task-relieving effect of 50% as suggested by Tavasszy (2016). Such an amendment of Regulation (EC) No 561/2006 will presumably enhance the resultant benefits from platooning even further by significant personnel cost cuts due to compulsory idle times which possibly become no longer necessary.

Finally, we evaluate our hierarchical planning-based heuristic approaches with reference to our joint optimization model in terms of fuel savings. As respects computational efficiency, the exact EU-TPP model will most likely be characterized by long computation times until an optimal solution – if at all after an acceptable time frame – is found. To this end, we perform a trade-off analysis opposing solution quality to processing time with regard to the introduced two-level matheuristics in this thesis. These are expected to provide good, near-optimal solutions within a reasonable amount of time.

All models are analyzed with regard to their behavior with different problem sizes, time windows and local starting situations of the trucks to derive important insights for the coordination of platoons. We are aware of the aspect that a random choice of the HDVs' respective origins, destinations and time window centers can heavily affect the solution quality, processing times and overall computational complexity of our problem instances. For this purpose, we run every model version with all four problem sizes and both time-window types for 30 times – each time with newly generated instances. After a maximum runtime of 3600 s, we stop each model run in case it has not finished its search for the best possible solution yet in order to evaluate the respective models' temporal performance within that preset time frame and to keep the experiments manageable. This is done for both the different-start as well as the single-hub calculations of our problems. In doing so, we can provide statistically well-founded statements from our experiments. Since the standard planning model without platooning would always lead to the same solution for the same route, irrespective of the time window size, we run this specific model only once per different- and same-start instance. Consequently, 2640 model runs are performed altogether.

Please note that we base our major investigations on the single manning versions of our modeling approaches only. The effect of multi manning on platooning is considered to be negligible in the problem instances at hand as the network size is too limited to derive sound statements from a comprehensive numerical study. It is thus subject to future work – just as well as extensive quantitative experiments relating to various aspects of fuel consumption, different shares of a possible task relief when trailing in the slipstream of a PL, varying wage levels and 'soft' travel time windows with lateness penalties, among other things. However, we will assess and discuss all these factors within the framework of a qualitative sensitivity analysis later on. Since they are expected to have a non-negligible influence on the coordination of platoons, their implications will be analyzed in an artificially controlled numerical setting.

5.1.3. Performance indicators

In order to derive well-founded conclusions from our assessment procedure, we still need to define appropriate performance indicators per instance. These are explained in the following. We assume that all denominators are unequal to zero.

Please note that we also use simple counting indicators which are not specifically defined here, e.g. the number of additionally scheduled waiting time steps or the number of mandatory breaks, among other things. Moreover, further explanations about the respectively required maturity levels of the specific instances' solutions for the calculation and comparison of the subsequent performance indicators (i.e. if they need to be solved to optimality or not) are provided in Appendix G.

In order to evaluate the maturity level of the generated solutions by Xpress after the preset runtime limit of 3600 s, we use the key figure below:

a) Optimality gap: Describes the difference between the current best solution found and the current best lower bound of the minimization problem in relation to the current best solution found by the optimizer.

$$\text{Optimality gap} := \frac{\text{best solution found-best bound}}{\text{best solution found}}$$

Following the default settings of Xpress, the best solution found is optimal when the optimality gap is smaller than or equal to 0.01%.

The suspected fuel savings potentials from platooning are probably the most convincing argument for politics, truck manufacturers and fleet managers to promote this new technology. Suitable key figures to this effect are defined as follows:

b) Percentage fuel cost savings: Describes the fuel cost difference between the standard benchmark model and the applied EU platooning approach (basic EU-TPP, SPH, PRH) in relation to the fuel cost of the standard benchmark model.

$$\text{Percentage fuel cost savings} := \frac{\text{standard fuel cost-fuel cost of EU platooning model}}{\text{standard fuel cost}}$$

It quantifies the fuel saving advantage of exploiting the slipstream effect by introducing the option to platoon within the EU.

c) Percentage change of fuel cost: Describes the difference between the EU-TPP's fuel cost (with or without a task relief) and those of a reference model in relation to the fuel cost of the reference model.

$$\text{Percentage change of fuel cost} := \frac{\text{fuel cost of EU-TPP version-fuel cost of reference model}}{\text{fuel cost of reference model}}$$

It displays the relative fuel cost shift in the presence of mandatory EU driving time restrictions or a hypothetical task relief.

- Reference model for basic EU-TPP: mere platooning model without the consideration of EU law
- Reference model for EU-TPP with task relief: basic EU-TPP

In order to compare our hierarchical planning-based approximation approaches with the exact model in terms of fuel cost savings, we use a similar performance indicator as the one applied by Larsson et al. (2015):

> d) Share of maximum fuel cost savings: Describes the fuel cost difference between the standard benchmark model and the applied matheuristic (SPH, PRH) in relation to the fuel cost difference between the standard benchmark model and the basic EU-TPP approach.
>
> $$\text{Share of maximum fuel cost saving} := \frac{\text{standard fuel cost} - (sub)\,\text{optimal fuel cost of heuristic}}{\text{standard fuel cost-optimal fuel cost of EU-TPP}}$$
>
> It checks the achieved fuel savings of the heuristics against those maximum ones of the joint optimization model.

Although the central focus of platooning lies on the generation of fuel savings by making use of a reduced aerodynamic drag, the time-dependent personnel costs play an important role as well – be it due to a potential task-relieving effect or because of additional pauses to facilitate the formation of more platoons. The required key figures for this TCO component are represented by:

> e) Percentage personnel cost savings: Describes the personnel cost difference between the basic EU-TPP and its version with a task-relieving effect in relation to the personnel cost of the basic EU-TPP.
>
> $$\text{Percentage personnel cost saving} := \frac{\text{personnel cost of EU-TPP-personnel cost of EU-TPP (task relief)}}{\text{personnel cost of EU-TPP}}$$
>
> It quantifies the wage-related savings potentials which are associated with a hypothetical adaptation of Regulation (EC) No 561/2006 in terms of a task-relieving effect for PFs compared to disregarding such an effect.
>
> f) Percentage increase of personnel cost: Describes the personnel cost difference between the applied EU platooning approach (basic EU-TPP, SPH, PRH) and the standard benchmark model in relation to the personnel cost of the standard benchmark model.
>
> $$\text{Percentage increase of personnel cost} := \frac{\text{personnel cost of EU platooning model-standard personnel cost}}{\text{standard personnel cost}}$$
>
> It indicates the increase of wage expenses for truck drivers due to platooning-related aspects like optional waiting times or more time-consuming split daily rest periods in the EU.

In the end, the new possibilities provided by platooning are reflected in a positive development of the total cost, which is measured as follows:

> g) Percentage total cost savings: Describes the difference between a reference model's total cost and those of the applied EU platooning approach (EU-TPP with or without task relief, SPH, PRH) in relation to the total cost of the reference model.
>
> $$\text{Percentage total cost savings} := \frac{\text{total cost of reference model-total cost of EU platooning model}}{\text{total cost of reference model}}$$
>
> It displays the resultant savings when aggregating the fuel- and wage-related cost effects of platooning.

- Reference model for basic EU-TPP, SPH and PRH: standard benchmark model
- Reference model for EU-TPP with task relief: basic EU-TPP, standard benchmark model

While it might also be interesting to know how many HDVs participated in a convoy throughout the planning horizon at all, we are rather interested in the amount of trucks which actually profited from the reduced air drag in a platoon. Following the Platooning Rate indicator defined by Liang et al. (2014), we therefore introduce a slightly modified key figure, taking the leading HDV out of consideration:

> h) Platoon Exploitation Rate (PER): Describes the overall distance covered in a slipstream-exploiting manner within a platoon by all trucks in relation to the overall distance covered by all trucks in the road network.
>
> $$\text{Platoon Exploitation Rate } (PER) := \frac{\text{total distance platooned in the slipstream (all trucks)}}{\text{total distance covered in the network (all trucks)}}$$
>
> It expresses which share of the overall traversed edges in the given highway network is covered by utilizing the slipstream of a preceding truck in a platoon. In other words: it indicates the platooning performance within the entire network in terms of actually exploited opportunities to platoon among all trucks.

The change of this performance indicator is also relevant to track its development under different circumstances:

> i) Change of Platoon Exploitation Rate (PER): Difference between the PER with the applied EU platooning approach (EU-TPP with or without task relief, SPH, PRH) and the PER with a reference model.
>
> $$\text{Change of Platoon Exploitation Rate (PER)} := \text{PER with EU platooning model-PER with reference model}$$

- Reference model for basic EU-TPP: mere platooning model without the consideration of EU law
- Reference model for SPH, PRH and EU-TPP with task relief: basic EU-TPP

However, the computational efficiency of our exact EU-TPP approach as well as of the two introduced matheuristics can only be assessed by taking the following two performance indicators into account during our analysis:

> j) Processing time: Measures the overall time in seconds from starting the respective model run until the solution output is finally generated. As this key figure also involves the time to load and prepare the input data for the optimization software's solution process, it can be slightly longer than the preset runtime limit of 3600 s.
>
> k) Share of EU-TPP processing time: Describes the heuristic's processing time in relation to the basic EU-TPP model's processing time within the preset runtime limit of 3600 s.
>
> $$\text{Share of EU-TPP processing time} := \frac{\text{processing time of heuristic}}{\text{processing time of EU-TPP}}$$
>
> It therefore expresses the matheuristics' processing time as a fraction of the exact EU-TPP's processing time.

If any of the above key figures is used as an average indicator, this refers to the mean value among the respectively performed model runs per type of coordination problem (i.e. the different- or same-start problem, with restricted or unrestricted time windows) based on a certain amount of trucks in the network. An average key figure commented with 'across all types of coordination problems' indicates the overall mean value per number of HDVs accordingly.

Many comparisons between certain problem sizes, instance types or models require the respective instances to be solved to optimality. As the case may be, some average key figures might thus be influenced by different underlying population sizes in one way or another. Hence, we want to point out that possibly occurring anomalies during the analysis could have their origin in this circumstance, at least to some extent. Nevertheless, it is our intention to exploit as much data as is available from our numerical computations instead of shrinking each comparison down to the lowest common denominator in terms of population size. This would waste some valuable information from the remaining optimally solved cases. In other words: we rather take the risk of losing some explanatory power between the problem sizes, models or instance types than within them, because this is considered to be of higher importance.

5.2. Validation

In order to demonstrate the functionality and operating principles of the EU-TPP, we validate our joint optimization model by means of a short controlled numerical study, before actually applying it within our extensive quantitative experiments. Hereto, we create artificial instances which are primarily based on the previously presented data settings and network to show desired effects. As the two heuristic approaches originate from the mathematical formulation of the exact EU-TPP itself and thus share similar modeling characteristics, only a brief validation of their respective differences is provided here. Tables 4, 5 and 6 show three exemplary scenarios along with the respective principles they are meant to validate. In the following, we explain the individual models' implementation results by Xpress and their basic effects step-by-step. Afterwards, the efficiency-raising character of the introduced pruning-based auxiliary constraint is proven as well. Please see Appendix A for a reference to the respective validations.

5.2.1. Major mechanisms of the exact EU-TPP model

First of all, we assume that penalty costs are extremely high (e.g. 1000 € per time step) and a potential task relief when being a PF is defined with 50%.

Trucks 1 and 2 in table 4 start at the same time step 0 from Munich to travel in a convoy to Salzburg, with truck 2 being the PF due to its higher vehicle index. Since truck 1 and truck 3 share the same route segment from Salzburg to Udine, the formation of a platoon would also be useful on this path. However, truck 3 can only start from step 7 on, while truck 1 could just continue driving. Here, an extra waiting time step of 15 min turns out to be favorable as the additional personnel cost for this short period (i.e. 3.75 €) are less than the savings offered by a jointly formed convoy (i.e. 6.48 €). So the model instructs the two vehicles to merge. As truck 3 has the higher vehicle index, it profits from the slipstream effect that is enabled by truck 1 until Udine. So even though this latter truck does not profit itself, it contributes to the reduction of the total fuel cost in the coordination system. This emphasizes the need for mutual compensation mechanisms.

Without an adaptation of the strict EU driving time legislation by politics in the presence of platooning, truck 3 would normally have to take a mandatory break after latest 18 time steps (i.e. 4.5 h) of accumulated driving on its way to Bologna, thus in Venice. Taking a 50% task-relieving effect of trailing as a PF into account though (like in Tavasszy, 2016), the EU-TPP only charges half of the actual driving time as counted driving time onto the driver's status. Consequently, no break needs to be taken by truck 3 from its origin to its destination. Contrasting this cost-cutting effect with the aforementioned additional waiting time of 15 min leads to additional savings in the field of personnel cost. All in all, running the single manning version of the EU-TPP with scenario 1 generates 3.00% fuel cost savings and even 1.43% wage-related savings compared to the standard planning model without platooning.

Table 4: Validation – scenario 1: EU-TPP (single manning)

Truck-ID	Origin	Destination	Earliest departure	Latest arrival	Effects to validate (single manning model)
Truck 1	Munich	Udine	0	19	role in platoon
Truck 2	Munich	Salzburg	0	6	waiting
Truck 3	Salzburg	Bologna	7	35	task relief (50%)
Truck 4	Stuttgart	Genoa	20	109	breaks / rest periods

Furthermore, the whole journey of truck 4 from Stuttgart to Genoa proves that compulsory breaks and daily rest periods are taken according to law. An 11 h rest in Innsbruck and a 45 min break in Bolzano are computed correctly. The long idle time only becomes necessary because the whole tour covers 42 time steps (10.5 h) of driving, so 1.5 h more than the threshold value for daily rest periods when being manned with one trucker. It is irrelevant if breaks or rests are taken first.

The second scenario demonstrates, among other things, that the EU-TPP suggests slightly longer detours for the sake of an increased fuel economy from platooning. In order to show this effect, we extend the edge length from Munich to Salzburg by one time step here. Penalty cost are set to 5.00 € per time unit, whereas we ignore a potentially lower charged driving time due to trailing in this scenario.

Now let us focus on truck 2 first. Assuming that a driver usually takes the shortest path, truck 2 would drive the southern route from Innsbruck to Udine via Bolzano, Verona and Venice with a mere driving time of 24 steps. However, our model recommends to use the 1 step longer northern path via Munich and Salzburg because a platoon can be formed with truck 1 for two highway segments from time step 0 on. The fuel savings generated by a train-like configured convoy outweigh the additional driver and fuel costs, thus justifying such a slight detour.

Next, we show that the EU-TPP allows for an intelligent and flexible design of tours in terms of mandatory breaks and daily rest periods when splitting rules are applied. Starting from Rome at step 0, truck 3 faces a long way ahead with 12 h on the road to reach Linz. This duration requires a driver to take at least a full break after latest 4.5 h, plus a full daily rest period after a maximum of 9 h accumulated time behind the steering wheel. In that special case though, scheduling partial breaks of 15 min in Perugia first and 30 min in Bologna second proves favorable to create a platoon with truck 4. As we will see shortly, truck 3 has no buffer in its entire time window from step 0 to 99 due to upcoming possibilities to platoon. So it can exploit the single break time step from his arrival in Perugia to the time window start of truck 4 with a partial break instead of waiting additionally. Going further in the routing plan, our optimization model identifies more opportunities for truck 3 to build a convoy, but under tough temporal restrictions. Nevertheless, the option to split the still required daily rest period into two separate parts renders these maneuvers feasible in the first place, which otherwise would have been impossible to realize. Even if a rest period split is always associated with at least 1 h more altogether, the financial benefits of platooning with truck 5 from Venice to Villach as well as from Salzburg to Linz with trucks 6 and 7 justify this increase in personnel cost. Concerning this matter, it must also be pointed out that the EU-TPP even recognizes the advantage of accepting a lateness penalty of 5.00 € for the last-mentioned truck in favor of utilizing the slipstream of others. Summing up, without the exploitation of splitting rules, many opportunities to platoon would be less attractive to be taken and even missed in this particular scenario.

Truck 8 finally gives prove to our model's ability to decide upon the correct and more cost-effective manning option as well. Although a crew of two drivers causes the double cost for wages, no breaks or daily rest periods have to be taken when they control the steering wheel alternately throughout their tour. After contrasting the double personnel cost for mere driving with a single trucker's wages for the sum of driving, a mandatory break and a required daily rest period, the implemented EU-TPP identifies double manning to be more attractive for truck 8.

Summing this scenario up, a comparison with the standard transport planning model from subsection 4.3.1 reveals fuel cost savings of 3.90%. Even if the total personnel cost turned out to be a bit higher because of the additional penalty cost as well as due to higher driver expenses for a detour and an extra hour of rest, the introduction of platooning still arranges for a 1.03% increased overall cost efficiency in the case at hand.

After all, we can conclude that our exact EU-TPP model actually unfolds the desired operating principles which we intended to incorporate in its formulation – finally resulting in the cost-efficient coordination of truck platoons. It is thus validated as an appropriate optimization framework for our quantitative investigations where we analyze the implications of different influencing factors on platooning and its associated benefits.

5.2.2. Characteristic effects of the different matheuristic approaches

With reference to our matheuristics, we provide another scenario 3 which is meant to show the main difference between these two based on the same setting. It is assumed that no task relief is granted for trailing, no penalties occur and the distance between Munich and Salzburg of 6 time steps is again increased by 1 step.

Table 5: Validation – scenario 2: EU-TPP (multi manning)

Truck-ID	Origin	Destination	Earliest departure	Latest arrival	Effects to validate (multi manning model)
Truck 1	Innsbruck	Salzburg	0	13	
Truck 2	Innsbruck	Udine	0	28	
Truck 3	Rome	Linz	0	99	detours
Truck 4	Perugia	Bologna	7	19	break / rest period splitting
Truck 5	Venice	Villach	39	51	lateness penalties
Truck 6	Salzburg	Linz	93	99	manning
Truck 7	Salzburg	Linz	92	98	
Truck 8	Stuttgart	Genoa	31	120	

Table 6: Validation – scenario 3: SPH and PRH

Truck-ID	Origin	Destination	Earliest departure	Latest arrival	Effects to validate (single manning model)
Truck 1	Munich	Venice	0	30	main difference:
Truck 2	Innsbruck	Bolzano	0	30	shortest path
Truck 3	Munich	Villach	0 vs. 100	30 vs. 120	vs.
Truck 4	Udine	Venice	0 vs. 100	30 vs. 120	platoon routing

Let us first consider the sub-scenario in which the earliest possible departure and latest possible arrival times of all four trucks are the same. The SPH correctly identifies the shortest route from Munich to Venice for truck 1 by travelling via Verona. Since truck 2 and the latter have both overlapping sub-routes and time windows, the heuristic recommends the two HDVs to merge for the common part of their journey in stage 2. Despite the already generated savings on this part of the network, our implemented PRH performs even better by focusing on another route option. As already pointed out in section 4.2, the platoon routing approach tries to exploit the theoretically most frequented segments in the road network without considering any temporal restrictions throughout the planning horizon. Since two platooning opportunities emerge when travelling to Venice via Villach – regardless of their temporal feasibility – the PRH prefers this route more than the shortest path. Although it takes 1 time step longer for truck 1 to reach its destination, the fuel cost savings enabled by the two actually feasible platoons with trucks 3 and 4 outweigh the additional costs quickly and make the PRH the more attractive approach for this sub-scenario.

In contrast, the PRH performs worse when the second version of scenario 3 is implemented, i.e. trucks 3 and 4 still share the same sub-routes with truck 1, but without any overlaps in their respective time windows. This leads to the aforementioned false route recommendation. The potentially expected platoons do not occur, whereas the chance to build a single convoy on the shortest path is actually missed as well. Consequently, the SPH turns out to be superior in this case because it is less sensitive towards such strong schedule differences.

All these specific scenarios clearly demonstrate that platooning opportunities can have a considerable impact on routing and scheduling decisions. As their interdependence is highly complex – even more when manning options, breaks and daily rest periods need to be considered as well – a remarkable computational effort to solve the exact EU-TPP to optimality already becomes apparent during our tests, whereas the standard EU benchmark model as a reference can be solved within just a few seconds as it only decides upon routing. Our matheuristics have finally been proven to show the desired functionality and can thus be utilized to address the issue of computational efficiency during our numerical experiments later on.

5.2.3. Significance of pruning-based auxiliary constraint

In subsection 4.4.1, we introduced an auxiliary constraint which is assumed to reduce the computational efforts by limiting the maximum deviation from the shortest path to a reasonable extent, taking the maximum possible fuel cost benefits from platooning on a detour into account. Before we actually apply this pruning approach within our experiments, its efficiency-raising character is tested and validated by means of the generated instances for 3 and 6 trucks in an unrestricted different-start setting. Both the single and double manning models' respective processing time performances are analyzed to this end. The associated results are shown in tables 7 and 8.

As can be seen in table 7, the single manning version of our EU-TPP performs much better in terms of processing time if the auxiliary constraint is actually applied. Even though all instances with 3 trucks can be solved to optimality both with and without pruning, the average processing time is about 20 s lower with the additional restriction. Only in 3 out of

Table 7: Analysis of pruning-based auxiliary constraint – single manning

Pruning	Number of vehicles	Average processing time [seconds]	Solved to optimality	No best solution found in time	(Sub-) Optimal solutions...	...with average optimality gap	Amount of longer processing times (solved to optimality)	Mean time longer [seconds]
With pruning	3 Trucks	36	30	0	0	0,00%	3	18
	6 Trucks	421	29	0	1	6,93%	0	0
No pruning	3 Trucks	56	30	0	0	0,00%	27	25
	6 Trucks	1438	22	0	8	6,89%	22	435

30 cases, the calculations take longer than without its application. Carrying on with the instances consisting of 6 trucks, the auxiliary constraint underpins its favorable impact on computational efficiency. Given the preset runtime limit of 3600 s, the average processing time of all 30 instances lies at 421 s with only 1 instance being left unfinished. While computations without pruning require more than three times this period on average though, even 8 instances are still left with an optimality gap. This aspect contributes essentially to the long average processing time. No case can be identified among those that have been solved to optimality where the constraint-applying version of the exact EU-TPP took longer. Quite the contrary, the mean temporal overhang is at 435 s without pruning for the optimally solved 22 instances.

Where the multi manning model is concerned, table 8 also supports the incorporation of our auxiliary constraint, albeit less obviously than in the single manning case at first glance. First of all, it becomes apparent that the double manning version requires significantly more computational efforts than the other one. This benefits our upcoming numerical experiments based on the single manning model in turn as the runtime limit of 3600 s is exploited more quickly when considering a team of truckers. Less mature and substantive outcomes would be the consequence. Solving instances with 3 trucks results again in all instances being solved to optimality, but with a relatively balanced proportion of longer processing times on each side. However, within those 17 cases in which pruning turns out to promote a quicker solution, the calculations take almost five times longer without pruning on average (83 s) than the other way around (17 s). The average processing time is thus about 40 s lower when incorporating a threshold restriction for detours.

Out of the 18 instances that have been solved to optimality with 6 trucks being coordinated without pruning, two thirds are finished 415 s earlier on average when applying the pruning constraint. Although there is not a big difference regarding the average processing times like in the single manning examples – also due to the fact that many instance runs are not yet terminated after the aforementioned runtime limit on both sides – the solution maturity is generally higher if pruning is considered. Without the auxiliary constraint, two instances more are not solved to optimality yet while also exhibiting a 2.27% higher gap among those unfinished cases with a current best solution on average. One instance is even left with no best solution found at all. Following the single manning examples, we assume that even larger differences would be visible if more cases were solved to optimality without a runtime restriction on the solution process.

On the whole, we can conclude that our pruning-based auxiliary constraint has a very positive effect on the models' required processing times on average. Especially the single manning version of our EU-TPP approach exhibits tremendous time savings for the tested instances. For this reason, its application within the subsequent computational study is highly justified. We are now prepared to focus on our numerical experiments in the next chapter in order to answer the research questions at hand.

6. Computational Study and Discussion

In this chapter, we finally analyze and evaluate the performance of both the exact EU-TPP and the two newly introduced matheuristics in terms of generated savings and computational efficiency. In doing so, we gain insights into the financial implications of exploiting the platooning technology in a – potentially also modified – European legal framework. Furthermore, a controlled qualitative sensitivity analysis relating to critical influence factors on platooning is conducted. Please see Appendix A for a reference to the underlying data and associated calculations.

6.1. Performance evaluation of the EU-TPP

The following subsections are dedicated to the numerical analysis of the optimization results which are generated by the exact EU-TPP model. After providing an overview of some general observations in conjunction with the single manning EU-TPP's performance, we investigate the major reason for bringing platooning into transport practice while also considering mandatory driving time restrictions in the EU: fuel savings. The effects of these strict rules on platoon coordination are worked out next. Finally, we assess the implications of a hypothetical legal adjustment of Regulation (EC) No 561/2006 in terms of a task-relieving effect for the driver of a following truck in a platoon to the amount of 50%.

6.1.1. General observations

Table 9 gives a summary on some general statistics for the three platooning models in comparison. It displays the different coordination problem types' respective solution maturity levels per problem size, optional waiting times taken for the

Table 8: Analysis of pruning-based auxiliary constraint – single manning

Pruning	Number of vehicles	Average processing time [seconds]	Solved to optimality	No best solution found in time	(Sub-) Optimal solutions…	…with average optimality gap	Amount of longer processing times (solved to optimality)	Mean time longer [seconds]
With pruning	3 Trucks	148	30	0	0	0%	13	17
	6 Trucks	1838	20	0	10	8%	6	300
No pruning	3 Trucks	188	30	0	0	0%	17	83
	6 Trucks	2016	18	1	11	11%	12	415

sake of platooning (incl. more time-consuming split daily rest periods) as well as the average processing times.

At first glance, it becomes immediately apparent that the mere platooning model without EU law-based constraints is more straightforward to solve than the exact EU-TPP. Much shorter average processing times and less unsolved instances are the consequence. Compared to its task-relieving variant, the basic EU-TPP exhibits shorter average processing times with many more cases where a (sub)optimal solution is already found after reaching the runtime limit of 3600 s. On the one hand, it has already been assumed before that incorporating mandatory breaks and daily rest periods in the EU-TPP would have a negative impact on computational efficiency. Without the inclusion of legal constraints, less local and temporal restrictions have to be considered which makes it much easier for the solver to find an optimal platoon routing and scheduling solution after a comparatively short period of time. On the other hand, including a task relief of 50% when following a PL in the model formulation results more difficult to solve than keeping the strict EU driving time law as it is – especially in the underlying road network graph where each edge has a length of 6 time steps. A 50% 'discount' on the actually charged driving time would allow a following driver to cover 3 more time steps per edge traversal without the need to take a mandatory pause period. Along with this aspect comes the critical point: platooning options, breaks and daily rests have to be recalculated in an ongoing manner. This means that platoons must be formed under consideration of EU law first, the task relief must be assigned to the PFs second, new breaks or rest locations / times need to be determined third and potentially new platooning options are found fourth, before the whole procedure starts anew or the entire system is finally optimized. Accordingly, the temporal performance when including a task-reliving effect for trailing in the slipstream turns out to be worse than otherwise.

Like assumed, increasing the number of trucks in the network from 3 to 12 generally leads to less instances being solved to optimality within the preset maximum runtime, accompanied by drastically increasing average processing times within that period. This can be reasoned by more possible platoon combinations that come into play, with each truck having its own local and temporal restrictions relating to origins, destinations and pause locations. The anyway complex solution process gains exponentially in complexity like this.

As far as both EU-TPP versions are concerned, there is a clear tendency that the different-start instances are computationally more challenging than the same-start cases, given comparable time window conditions. The latter ones largely exhibit shorter processing times along with more model runs being finished at the best possible solution after the maximum runtime on average. Although we are aware of the fact that randomly generated model inputs like origins, destinations, earliest possible departure and latest possible arrival times have a non-negligible impact on the solution procedure's duration, there is a simple explanation for the same-start setting's temporal superiority: the trucks do not need to be coordinated to a common meeting point first in order to merge like in the different-start case. This reduces computational complexity to some degree.

However, the mere platooning model without the consideration of binding EU transport law seems to behave differently. Applying a same-start coordination approach results slightly more time-consuming than a different-origin one. We suppose that excluding mandatory breaks and daily rest periods from the model formulation brings the aforementioned issue with random baseline situations further to the fore. Less favorably located starting points and destinations could be one reason for this observation, i.e. the solver might be undecided between alternative, equally long routes like between Venice and Munich (either via Bolzano or via Villach), for example. We see no other evident explanation here.

Furthermore, the influence of time window sizes on processing times and solution maturity seems to be relatively insignificant. There is no clear trend apparent which proves instances with the fully available planning horizon or restricted time windows to be computationally really superior towards the other. Even though the restricted instance types of both exact EU-TPP models show many more cases where no best solution is found at all after the runtime limit is reached, the average processing times and the amount of (sub)optimal solutions with their gaps leave a more ambiguous impression.

Referring to additionally scheduled time steps for optional waiting times or for reasons of rest period splitting, table 9 reveals another very interesting aspect for all the instances that have been solved to optimality within the maximum runtime. While it is less surprising that no extra time steps are planned at all with the mere platooning model, we can identify a significant increase in their appearance when considering a task-relieving effect of 50% for PFs in the EU-TPP – despite the fact that more instances of the basic EU-TPP version have been solved to optimality than conversely. This outcome clearly demonstrates that Regula-

Table 9: Overview of general output statistics – part 1

Model	Type of coordination problem	Number of vehicles	Solved to optimality	No best solution found in time	(Sub-) Optimal solutions...	...with average optimality gap	Additional waiting time / rest steps (solved)	Average processing time [seconds]
Basic EU-TPP	Different start (full)	3 Trucks	30	0	0	0.00%	0	36
		6 Trucks	29	0	1	6.93%	1	421
		9 Trucks	21	0	9	3.70%	1	1533
		12 Trucks	14	0	16	6.17%	2	2672
	Different start (restricted)	3 Trucks	30	0	0	0.00%	0 / 4	32
		6 Trucks	28	0	2	1.63%	1	603
		9 Trucks	26	0	4	18.71%	2	1095
		12 Trucks	15	6	9	8.26%	1	2469
	Same start (full)	3 Trucks	30	0	0	0.00%	0	30
		6 Trucks	30	0	0	0.00%	0	195
		9 Trucks	25	0	5	6.13%	0	1054
		12 Trucks	20	3	7	7.41%	0	1945
	Same start (restricted)	3 Trucks	30	0	0	0.00%	0	46
		6 Trucks	29	0	1	3.84%	0 / 4	310
		9 Trucks	21	1	8	19.00%	0	1335
		12 Trucks	20	5	5	4.32%	0	1866
EU-TPP (50% task relief)	Different start (full)	3 Trucks	30	0	0	0.00%	0	79
		6 Trucks	25	1	4	3.86%	3	909
		9 Trucks	22	2	6	6.72%	8	1899
		12 Trucks	11	3	16	8.26%	5	2812
	Different start (restricted)	3 Trucks	30	0	0	0.00%	0 / 4	83
		6 Trucks	26	0	4	6.30%	4	909
		9 Trucks	19	6	5	4.28%	6 / 4	1922
		12 Trucks	13	10	7	14.92%	7	2571
	Same start (full)	3 Trucks	30	0	0	0.00%	12	37
		6 Trucks	27	0	3	2.65%	20	666
		9 Trucks	21	2	7	3.14%	14	1484
		12 Trucks	16	4	10	2.89%	6	2366
	Same start (restricted)	3 Trucks	30	0	0	0.00%	6	42
		6 Trucks	28	0	2	1.53%	29	527
		9 Trucks	22	7	1	2.80%	24	1401
		12 Trucks	19	10	1	15.10%	21	1814
Platooning (without EU restrictions)	Different start (full)	3 Trucks	30	0	0	0.00%	0	28
		6 Trucks	30	0	0	0.00%	0	120
		9 Trucks	30	0	0	0.00%	0	314
		12 Trucks	29	0	1	0.88%	0	986
	Different start (restricted)	3 Trucks	30	0	0	0.00%	0	31
		6 Trucks	30	0	0	0.00%	0	96
		9 Trucks	29	0	1	0.61%	0	398
		12 Trucks	30	0	0	0.00%	0	634
	Same start (full)	3 Trucks	30	0	0	0.00%	0	33
		6 Trucks	30	0	0	0.00%	0	274
		9 Trucks	28	0	2	20.92%	0	561
		12 Trucks	25	2	3	12.28%	0	1325
	Same start (restricted)	3 Trucks	30	0	0	0.00%	0	37
		6 Trucks	30	0	0	0.00%	0	125
		9 Trucks	30	0	0	0.00%	0	299
		12 Trucks	28	2	0	0.00%	0	953

tion (EC) No 561/2006 does not only represent an obstacle for platooning, but also contributes positively to the formation of platoons. Indeed, the EU-TPP instances without a driving time 'discount' on edge traversals as a PF also use optional pause times next to the anyway prescribed idle times to favor platooning. However, as the actual application of a task relief requires less mandatory breaks and daily rest periods (if any at all) to be scheduled, there are suddenly less pauses which could be exploited as opportunities to wait for each other in order to form a fuel-efficient convoy. The artificially extended trip durations can thus be interpreted as further options to be able to platoon at all – provided that the therefore accruing extra personnel cost do not excel the fuel cost savings from platooning. In contrast, the fact that the mere platooning model without EU restrictions does not exhibit any additional pause times can be attributed to the anyway higher flexibility of trucks in its solved instances. No breaks or daily rest periods need to be taken into account. This offers more opportunities for smart departure time scheduling so that the involved HDVs can be merged more easily to form a platoon.

As can be seen, additional pauses are particularly scheduled in case of same-start instances when a task relief is granted. This seems counterintuitive because we would assume more voluntary waiting times to occur in a different start-setting like in the basic EU-TPP model with no task relief where trucks have to meet first in order to be able to platoon. Of course, generally less instances have been solved to optimality with different origins at hand. This aspect could indeed contribute to such an observation. However, starting from a joint location also means that a task relief can be granted from the beginning. So when the leading driver requires a first break – and so would the following driver as well without the presence of a task-relieving effect – the PF could either continue his journey without platooning or wait for the PL to proceed with the convoy on their common route segments.

Moreover, we identify a very slight tendency among both EU-TPP variants' instance types that restricted time windows lead to more extra waiting times than a fully available planning horizon. We suppose that this is due to the fact that restricted time frames lack the required flexibility in terms of fully overlapping time windows, where smart departure time scheduling is easier. A later earliest possible start of one truck, for example, could make another already travelling HDV wait an additional time step to form a joint convoy over a common route segment. Similar difficulties could also appear with the full flexibility though, e.g. when drivers are forced to depart earlier due to the long duration of their tour which covers almost the entire planning horizon. Such circumstances are also to blame for the observed waiting times in the less restricted different-start problem, but to a more limited extent than with stricter time windows. Hence, we conclude that instances with partly overlapping travel time frames face a slightly higher probability of additional waiting times to be scheduled than in case of fully overlapping ones. The unrestricted same-start case ultimately exhibits no optional waiting times at all because trucks can depart jointly and take their mandatory breaks or daily rest periods together at the same locations.

As generally more instances are left unsolved to the end with an increasing number of coordinated trucks, we are not able to make proven statements about the interrelation between the number of extra waiting time steps and the problem size from our experiments. However, we point out that more vehicles could mean both more or less voluntary pauses for platooning purposes as it is not always clear which specific new opportunities emerge from a local and temporal point of view. Please note: Optional waiting time steps have been assigned to the binary decision variable $fifmin_{v,i,m}$ instead of $w_{v,i,m}$ in some very few cases that we identified when having a closer look at the output data. As these are mostly scheduled for a maximum of 1 time step in our setting (which also corresponds to the duration of a first break part), the chosen model formulation could not entirely prevent this from happening with constraint (8). Nevertheless, the models' results are correct either way and lead to the exact same decisions with regard to routing, scheduling and platooning. Therefore, we decided to include these waiting times in table 9.

> Summing up our initial observations based on the performed experiments for the exact EU-TPP model formulation, we can conclude that:
>
> ... increasing the number of trucks to be coordinated in the highway network leads to longer processing times and a lower solution maturity on average.
>
> ... the anyway high computational complexity of the basic EU-TPP rises even further when a 50% task relief for following drivers in a platoon is considered.
>
> ... different-start instances are generally more difficult and time-consuming to solve than their same-start counterparts.
>
> ... taking a task relief of 50% into account results in more additional waiting times to be scheduled for the sake of platooning, especially in a same-start setting.
>
> ... mandatory breaks and daily rest periods have the potential to not just restrict, but also favor the formation of fuel-efficient platoons.
>
> ... there is a slightly higher probability of optional waiting times to occur when the trucks' respective time windows are restricted and just partly overlapping.

6.1.2. Basic financial implications of EU-constrained platoon coordination

The main driver for the merger of trucks to platoon is the generation of fuel cost savings by exploiting the slipstream effect behind a preceding vehicle. Thus, we want to investigate these key savings potentials provided by a joint routing and scheduling approach with the basic EU-TPP model in more detail next. To this end, figure 10 illustrates the average percentage fuel cost savings per type of instances and problem size, derived from our model runs performed by Xpress.

As can be seen at first sight, substantial fuel economies can be achieved by enabling trucks to platoon within the road network. The average percentage fuel cost savings range from 0.84% in the restricted different-start case up to 9.33%

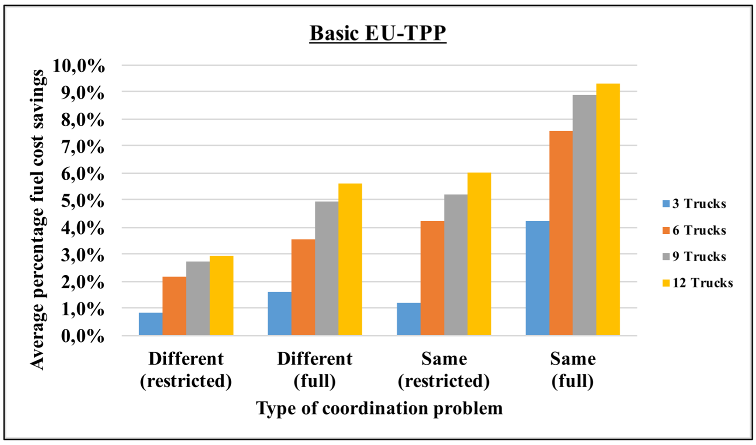

Figure 10: Average fuel cost savings by using the concept of truck platooning

for the fully flexible same-start instances which seem to be financially most superior. A maximum financial advantage of even 10.83% can be identified at best.

While narrow time windows rather impede the formation of platoons in both start versions, more temporal flexibility acts highly promotional on the fuel-related benefits from platooning. There is more freedom in planning with regards to departure time and pause period scheduling because the tour schedules have a higher degree of being overlapped. Hence, common edge traversals in a platoon are much easier to realize than in the restricted case. It is therefore obvious that the generated savings are much higher with an unrestricted planning horizon.

Across all four problem types, drastically increasing cost efficiencies can be reported when more trucks enter the system. A rising vehicle density implies that the probability of fuel-efficient convoys to be formed rises as well since it becomes less difficult to find another HDV with shared route segments and compatible temporal constraints. Hence, the number of platoon-capable trucks in the coordination network acts a very important part for the successes of platooning.

This conclusion can also be drawn and substantiated by analyzing figure 11 which shows the experiments' results in terms of PER for the different types of coordination problems. As the number of coordinated trucks increases, more HDVs can drive in close vicinity within a convoy and thus more vehicles are actually able to exploit the slipstream effect of their preceding trucks as a consequence. Doubling the amount of vehicles from 3 to 6 unexceptionally exhibits the largest growth in PER across all four instance types – with a more than 20% increase for both same-start cases and even a multiplication for its explicit restricted version from 7.90% to 28.27% by a factor of 3.58. Such a steep increase can be traced back to the necessity of a certain threshold amount of vehicles where the benefits of platooning can really take effect. There are still a lot of single 3-truck instances which do not lead to any platoon formations at all due to the lacking amount of potential convoy partners, especially in the different-start problems. Since the few available platoon-ready vehicles might additionally be widely spread throughout the network in the latter case, it is more probable that adding further trucks results in a highly positive effect on the average PER and the almost synchronously rising average percentage fuel cost savings.

However, it can also be observed that the relative increase in the average PER is slowly flattening as even more trucks take part in the platooning network. This suggests that the platoon-related average percentage fuel cost savings will probably even themselves out as soon as a particular network saturation is reached – asymptotically converging to the maximum possible fuel reduction for a PF of 15% at some point. Consequently, platooning calls for a certain threshold density level of platoon-capable trucks in the market in order to effectively take advantage of its entire fuel saving potentials.

As we do not consider any limit for the number of trucks within a platoon, it might be worth mentioning that the increases in average PER and percentage fuel cost savings could prove smaller when such a maximum limit is imposed by politics. More HDVs would actually have to take a leading position instead of exploiting the slipstream effect. This aspect should be considered in future research.

Similar to the fuel savings perspective, we see the negative implications of restricted time windows on the share of platooned edge traversals now. But while the difference in PER remains at a rather constant level of around 20% for the same-start problem versions, we recognize that the relative advantage of a fully available planning horizon in the different-start case is much lower with just a few trucks to be coordinated. The few available vehicles' local dispersion along with a low network saturation makes differences in feasible trip schedules almost negligible as it is anyway difficult to find merging partners compared to a same-start setting.

Taking the above figures into account, let us now focus on the type of coordination in terms of starting locations. In order to get deeper insights into the data, we have a closer look at the generated results' distribution and development per type of instances. Figure 12 displays the percentage fuel

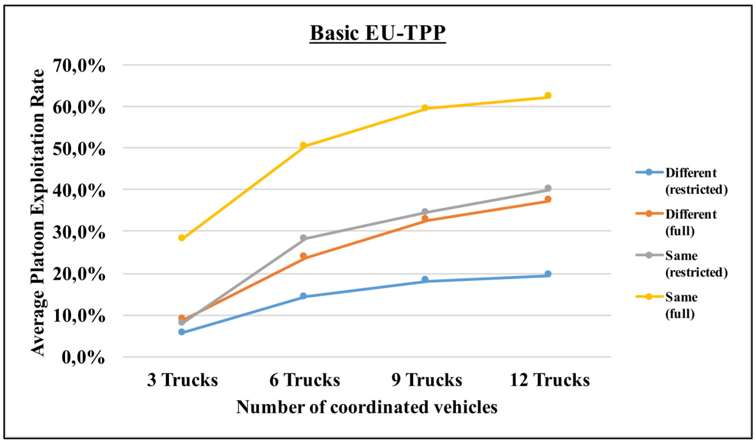

Figure 11: Development of average Platoon Exploitation Rates

cost savings for the respective problem sizes by means of boxplots[2] and average values.

The dashed-represented average percentage fuel cost savings development per instance type is well in line with the synchronous average PER graph from figure 10, emphasizing the impact of an adequately saturated network for platooning.

It becomes particularly evident from all three figures 10, 11 and 12 that starting from the same origin location leads to much higher platoon-related fuel cost savings, irrespective of the available time window cases. Although the unrestricted different-start instances still show a similar percentage fuel economies pattern to the restricted same-start problem with average values ranging from 1.19% for 3 trucks to 6.01% for 12 trucks, their respective counterparts exhibit large differences: the resultant savings are almost just half as large when coordinating HDVs from different origins on average. Moreover, the levels of both the minimum and maximum values observed for the percentage fuel cost savings are significantly higher when starting from the same nodes – ultimately resulting in minima around 6% for 6 trucks upwards and a maximum value of even 10.83% for 12 trucks in the bottom left corner graph. This considerable level of discrepancy can be explained by the fact that trucks have to merge at a common meeting point first in order to be able to platoon in a different-start setting. Same-start instances in turn can focus more on the temporal dimension of tour planning while relying on an inherently much higher probability of finding compatible platooning partners from the departure on.

However, the major impressions from figures 10, 11 and 12 all reveal that the coordination of trucks from the same starting nodes with the full planning horizon of 120 time steps available clearly outperforms all the other instance types. Almost the threefold percentage fuel cost savings can be achieved for problem sizes of 3 trucks compared to the different-start version on average. A maximum degree of flexibility along with ideal local preconditions for platooning arranges for remarkable fuel savings, even with relatively few vehicles to be coordinated in the network. The yellow curve in figure 11 impressively underpins the superiority of such an approach: with an average PER of up to 62.20% for 12 trucks in the network and a total maximum at 72.22%, it offers the most platooning opportunities by far – being up to 26.67% ahead of the corresponding different-start type on average. It should also be mentioned though that different-start instances are also highly affected by the respective trucks' randomly generated origin and destination nodes. A less favorable location pattern could actually allow for relatively few platooning opportunities.

After all, the impressive fuel savings generated among all four types of coordination problems raise the question of their average impact on the total cost savings structure when involving the associated wage expenses in the trip calculations. Table 10 discloses the respective results for this purpose. As hardly any additional waiting times or split daily rest periods are taken for the sake of platooning compared to the standard planning model in the EU without any platooning option (see also table 9), the average percentage increase of personnel cost with the conventional EU-TPP can rather be neglected. Thanks to smart scheduling, the amount of such optional idle periods can be kept at a minimum level.

Consequently, the average percentage total cost savings are almost fully attributed to the mere fuel-saving effect of platooning. We can thus make identical observations and derive analog conclusions as before with those relating to fuel only.

In the end, it needs to be stated that our central EU transport law-based platooning model is proven to work most effectively – generating considerable fuel cost savings while also taking mandatory driving time restrictions into account.

> Summing up our conventional EU-TPP-based investigations with respect to the fuel-related financial benefits of platooning in the EU, we can conclude that:

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[2] Please note that we follow the boxplot convention of using the minimum and maximum values as whiskers next to the lower quartile, median and upper quartile within the framework of this thesis.

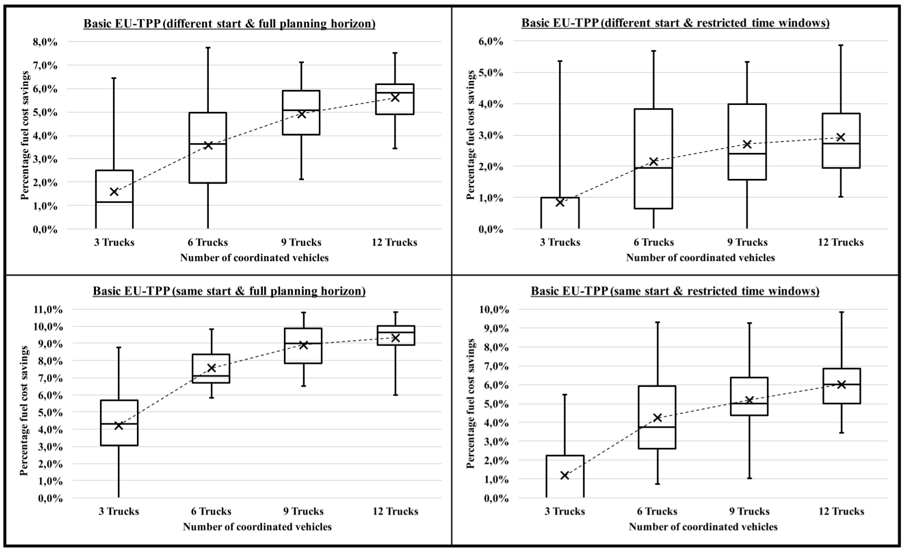

Figure 12: Fuel cost savings for each type of coordination problem

Table 10: Influence of platooning on the personnel and total cost structure

Number of vehicles	Average percentage... (increase of...)	Different start (restricted)	Different start (full)	Same start (restricted)	Same start (full)
3 Trucks	...total cost savings (...personnel cost)	0.44% 0.08%	0.92% 0.00%	0.68% 0.00%	2.59% 0.00%
6 Trucks	...total cost savings (...personnel cost)	1.15% 0.03%	2.00% 0.01%	2.49% 0.05%	4.61% 0.00%
9 Trucks	...total cost savings (...personnel cost)	1.55% 0.03%	2.72% 0.01%	3.03% 0.00%	5.43% 0.00%
12 Trucks	...total cost savings (...personnel cost)	1.76% 0.02%	3.44% 0.04%	3.56% 0.00%	6.02% 0.00%

...platooning can lead to substantial fuel cost savings on average – finally resulting in considerable total cost savings as well.

...coordinating a larger number of platoon-capable vehicles in the network generally leads to a higher PER with increasing average percentage fuel cost savings.

...an initially steep, but flattening increase in PER and average percentage fuel cost savings emphasizes the significance of a certain threshold amount of trucks in the platoon coordination system to effectively exploit the potentials of platooning.

...more restricted time windows result in less percentage fuel cost savings on average due to a lack of temporal flexibility.

...much higher fuel cost savings can be achieved with a same-start coordination approach on average due to its inherent local advantage for platoon formation.

6.1.3. Impact of mandatory breaks and daily rest periods on platooning

In the previous subsection, we used our introduced EU-TPP model which considers the truck drivers' compliance with Regulation (EC) No 561/2006 when coordinating HDVs in a platoon-favoring way. Nevertheless, we assume that compulsory breaks and daily rest periods have a non-negligible effect on the formation of platoons – be it in a favorable or unfavorable manner. In order to evaluate their impact on platooning by means of the basic EU-TPP, table 11 demonstrates the resultant change of the PER from a comparison with the mere platooning model without the consideration of strict EU driving time legislation. Since the exact same time windows are taken as a basis for both models, we expect substantially less platooning benefits in the presence of time-consuming mandatory breaks and daily rest periods due to an inherent lack of temporal flexibility.

On the one hand, we observe relatively low average PER changes in general with at most 3.91% for the restricted different-start problem with 6 trucks to be coordinated. On the other hand, though, some maximum values indicate a larger impact of mandatory pause times, peaking at 23.08% for the smallest problem size in the restricted same-start case. The resultant implications of changes in PER for the fuel cost structure can be derived from table 12.

Still, even though the maximum percentage fuel cost changes might suggest at least mentionable drawbacks from the obligation to take required breaks or daily rest periods in some cases, the average values show a rather moderate hypothetical advantage if pauses were not necessary – especially given the fact that remarkable savings can anyway be generated with the EU-TPP (see previous subsection).

The generally notable large discrepancies between the averages and the associated maxima in both tables can be traced back to the fact that most solved instances actually face just small (if at all any) decreases in PER when considering Regulation (EC) No 561/2006. We can even identify two specific examples of the same instance in which the necessity of a mandatory break leads to more platooned edge traversals and less fuel cost than without EU law: run 24 of the restricted different-start problem with 6 and 9 trucks. Herein, a required break along with one optional waiting time step helps truck 4 with bridging the temporal gap until the earliest possible departure of the next platooning partner (truck 3) is met. This allows truck 4 to also seize the opportunity to meet another HDV (truck 5) at that vehicle's latest possible platoon formation chance beforehand. But without the compulsory break, truck 4 is just able to decide between the two alternatives as the required optional waiting time to join both trucks would be too long – and thus too costly from a wage perspective. Consequently, the mere platooning model acts less favorably than the basic EU-TPP in such cases. Although these are the only instances with a positive change in PER that we can find in our experimental results, they clearly prove that mandatory pause times can actually represent a natural and real chance for platoons to be formed at all. We also infer from these findings that the relatively small negative impact of prescribed breaks and daily rest periods on platoon formation among all kinds of problem instances can be reasoned with that as well. The supposed impeding character of time-consuming pauses can actually be exploited for the sake of platooning by allowing trucks to wait for each other throughout their current tour.

Another aspect which becomes apparent is the comparatively larger influence of mandatory EU driving time regulations on the restricted problem types. While those cases with the full planning horizon available can still rely on an increased level of flexibility in the presence of breaks or daily rests, the anyway restricted time frames are additionally constrained with time-consuming pauses now. So it is obvious that compulsory idle times have a larger impact on the emergence of platoons when the available time windows are already narrow.

Furthermore, the last columns in both tables show no changes at all with stringent EU driving time regulations coming into play. This can again be reasoned by the advantageous starting situation which exists when the trucks are both coordinated from the same origin node and face less restricted transport schedules. Like this, it does not matter for the formation of fuel-efficient convoys whether required breaks or daily rests need to be taken or not. Firstly, the vehicles can already platoon in a temporally flexible manner from the departure on and thus do not have to meet first. And secondly, the required pause times can be scheduled at the same locations before jointly continuing the drive in a platoon throughout the trip. Hence, the binding legislation on driving times in the EU has no influence on the occurrence of platooning in such a setting at all. As regards the restricted same-start problem though, we see a slightly different outcome due to the existent temporal limits for the trucks' respective departures and arrivals. But all in all, the coordination from different starting nodes turns out to be a little more vulnerable to the impact of Regulation (EC) No 561/2006 for the aforementioned reasons.

Finally, it should be mentioned that there is no particular pattern visible relating to the influence of compulsory driving time restrictions on platooning with more vehicles entering the coordination system as the effects even themselves out.

> Summing up our assessment regarding the implications of mandatory breaks and daily rest periods for platooning in the EU, we can conclude that:
>
> . . . compulsory pauses display a noticeable, albeit relatively small negative impact on platooning within our experiments on average.
>
> . . . mandatory idle times can actually represent real chances to be able to form fuel-efficient truck platoons at all.
>
> . . . anyway restricted time windows are more prone to the consequences of additional constraints imposed by strict EU transport law.
>
> . . . the obstructive effect of mandatory breaks and daily rest periods is less apparent when trucks are coordinated by a same-start approach.

6.1.4. Consequences of granting a 50% task relief for followers in a platoon

Since the trucks in a platoon other than the leading one work semi-autonomously thanks to substantial advances in sensor and communication technologies, less and less driver attention is required on the way to full autonomous driving. After examining the influence of mandatory breaks and daily rest periods on the coordination of fuel-efficient platoons in the EU, it is now about time to investigate the implications of a quite possibly introduced task-relieving effect for followers in a convoy. A hypothetical driving time 'discount' of 50% when trailing in the slipstream of a preceding truck is expected to notably affect the necessity of taking such pauses which might influence the fuel saving potentials from platooning in turn. Table 13 outlines the consequences of such a scenario for the PER by contrasting it with the conventional EU-TPP approach without any task relief.

Table 11: Change of Platoon Exploitation Rate under consideration of mandatory driving time restrictions in the EU

Number of vehicles	Value	Different start (restricted)	Different start (full)	Same start (restricted)	Same start (full)
3 Trucks	Average	-1.51%	-0.76%	-2.07%	0.00%
	Max	-11.11%	-8.33%	-23.08%	0.00%
6 Trucks	Average	-3.91%	-0.83%	-3.21%	0.00%
	Max	-14.71%	-3.85%	-14.29%	0.00%
9 Trucks	Average	-3.74%	-0.83%	-2.70%	0.00%
	Max	-14.63%	-2.94%	-12.20%	0.00%
12 Trucks	Average	-3.41%	-1.29%	-1.56%	0.00%
	Max	-10.91%	-3.70%	-7.69%	0.00%

Table 12: Change of fuel cost under consideration of mandatory driving time restrictions in the EU

Number of vehicles	Value	Different start (restricted)	Different start (full)	Same start (restricted)	Same start (full)
3 Trucks	Average	+0.23%	+0.12%	+0.33%	0.00%
	Max	+1.69%	+1.30%	+3.67%	0.00%
6 Trucks	Average	+0.61%	+0.13%	+0.51%	0.00%
	Max	+2.28%	+0.60%	+2.24%	0.00%
9 Trucks	Average	+0.58%	+0.13%	+0.43%	0.00%
	Max	+2.29%	+0.46%	+1.95%	0.00%
12 Trucks	Average	+0.53%	+0.21%	+0.25%	0.00%
	Max	+1.69%	+0.60%	+1.21%	0.00%

As can be seen, there is no clear-cut or specific pattern for all the different types of instances and problem sizes apparent at all. While the implemented task relief can have a boosting effect for fuel-efficient edge traversals in a platoon of up to 13.79% compared to the basic EU-TPP, we can identify an even 10.71% lower PER in the most extreme negative case. Translated into percentage fuel cost, this leads to a change of up to -2.16% at best and up to +1.76% at worst accordingly. The relatively wide range of the irregularly occurring fuel-related effects from a task relief, which result in low average values around zero, has its explanation in the inherent character of such a legislative amendment. On the one hand, less charged driving times can be used to extend the non-stop covered route length before actually being obligated to take the first mandatory pause. This allows to either platoon over a longer common route segment or to seize the chance of joining another convoy – both ultimately leading to a higher PER with higher fuel economies. But on the other hand, the potentially lower amount of compulsory breaks or daily rest periods also reduces the previously described natural chances to meet each other for platooning purposes. This is also the reason why we identified more additional waiting times to occur in the task-relieving version of the EU-TPP in subsection 6.1.1. However, there is no incentive to keep the PER high if the potential personnel cost savings from no longer necessary idle times turn out to be much more attractive. A stringent pattern in the results of table 13 is therefore not visible.

What stands out in the last column of this table is solely the fact that unexceptionally lower or at best equal shares of the network are traversed in a slipstream-exploiting manner compared to the equivalent case where no 50% task relief is granted. As we have learnt from the previous subsection that mandatory breaks or daily rest periods do not affect the platoon formation in a fully flexible same-start setting at all, there is no further possibility to increase the PER and the resultant fuel cost savings by means of a task relief. Their values can only stay equal or decrease due to the fact that leading trucks would have to take their first compulsory pause times earlier than the following HDVs now. These ones can then choose whether to wait as well or to continue travelling without the former PL.

Consequently, we can derive from these observations that a task-relieving effect for PFs does not necessarily lead to more fuel-related benefits from platooning. As regards the personnel cost in comparison with the basic EU-TPP's wage-related expenses though, figure 13 illustrates a much more convincing and highly promising impact on the cost structure of fleet managers across all types of coordination problems and amounts of vehicles.

At first glance, it stands out that each graph consistently displays relatively low medians of up to 3.90% accompanied

Table 13: Change of Platoon Exploitation Rate under consideration of a 50% task relief compared to the basic EU-TPP

Number of vehicles	Value	Different start (restricted)	Different start (full)	Same start (restricted)	Same start (full)
3 Trucks	Average	+0.28%	+0.30%	+0.26%	-0.53%
	Min	0.00%	-7.14%	0.00%	-8.33%
	Max	+8.33%	+8.33%	+7.69%	0.00%
6 Trucks	Average	+0.48%	-0.56%	+1.48%	-1.61%
	Min	-3.45%	-10.34%	-3.70%	-10.00%
	Max	+4.17%	+3.85%	+13.79%	0.00%
9 Trucks	Average	+0.64%	-0.87%	+0.35%	-1.73%
	Min	-3.12%	-4.76%	0.00%	-10.71%
	Max	+10.53%	+2.50%	+3.45%	0.00%
12 Trucks	Average	+0.46%	+0.23%	-0.49%	-1.73%
	Min	-4.35%	-2.27%	-5.56%	-8.33%
	Max	+8.51%	+2.38%	+5.00%	0.00%

by maximum percentage personnel cost savings of up to even 31.86%. These literal ‘jumps’ stem from suddenly eliminated daily rest periods which would normally take a lot of precious time. They are also to blame for the relatively large gaps between the averages and the medians. Indeed, the much shorter and less costly breaks might become no longer necessary through the introduction of a task relief as well. However, the financial impact of their omission is rather small in comparison with those cost-efficiencies generated by redundant daily rests which do not need to be taken anymore. Ultimately, the vast majority of the analyzed and optimally solved cases exhibits either comparatively small wage savings from these left out breaks or none at all – explaining their much lower, but still remarkable overall personnel cost savings level.

Similar to the mere fuel-based investigations with the basic EU-TPP model before, a slightly lower personnel cost advantage can now be observed for the problems with restricted time windows. Again, this can be reasoned with the inherent lack of temporally overlapping trip schedules which naturally lead to a lower PER on average. Consequently, exploiting a task-relieving effect results more difficult.

Having a closer look at the instances with 3 coordinated trucks in figure 13 reveals that the wage-related impact of a task relief only takes noticeable effect with a certain threshold amount of vehicles in the network, especially in the different-start cases. Their maximum values are just at 3.87% while more than three quarters of their instances show no personnel cost savings at all. But then again, the same-start problems exhibit at least large maxima of up to 29.19% due to their favorable local and temporal starting situations where platoons can be formed more easily. This circumstance thus allows to better exploit the task-relieving effect of platooning, whereas the previously described lack of a high enough PER in a different-start setting with only 3 trucks naturally leads to smaller related benefits. We want to remind that a certain threshold number of trucks is reached much quicker and easier when coordinating trucks from the same origin node.

One might say now that more HDVs in the system automatically means that more percentage personnel cost savings occur. But figure 13 is less explicit here which makes us believe that this is only partially true for the already described reason above: a task relief can theoretically lead to a both higher or lower rate of platooned edge traversals and is therefore less precise with regard to an estimation of the associated personnel cost efficiencies. The lack of instances that are solved to optimality with an increasing problem size could also contribute to this observation. Nevertheless, we expect that on the whole, the coordination of more vehicles will generally have a stimulating effect on the wage-related savings potentials from truck platooning.

Moreover, looking closer at the upper quartiles of the 9- and 12-truck problem sizes in particular exhibits a larger share of instances with higher percentage personnel cost savings in the different-start settings than in the corresponding same-start ones. Of course, we need to bear in mind that the specific road network constellation with its explicit starting conditions for trucks can also affect our experiments' outcomes. But there is another logical explanation to this observation as well. With small problem sizes, exploiting the task-relieving effect of trailing as a PF from the same node is much easier to realize because of the aforementioned reasons. However, as more trucks enter the system, the chances to exploit such an effect also rise for the different-start problems. Simultaneously, more PFs in the same-start instances are willing to wait some extra time steps to continue platooning with the meanwhile pausing PL – despite their more easily granted task relief. Being in line with the conclusions drawn in subsection 6.1.1 relating to optional waiting times, this arranges for additional wage expenses and can thus have a lowering and consolidating effect from a personnel cost savings perspective.

Figure 14 substantiates these findings by displaying the

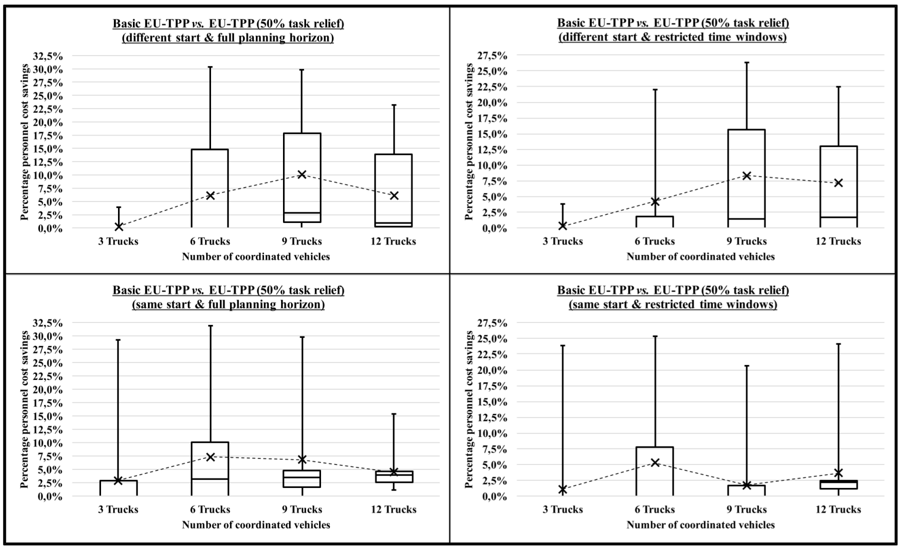

Figure 13: Personnel cost savings for each type of coordination problem

total amount of mandatory idle times that are rationalized for all the optimally solved instances when a task relief of 50% is applied. The dashed fields indicate the differences compared to the basic EU-TPP. Please note that fewer instances are solved to optimality with growing problem size, explaining the decreasing shape of the graphs at some point.

Despite the fact that more compulsory breaks are actually omitted in the same-start cases, this effect is relatively used up by the aforementioned extra waiting times that are scheduled for the sake of fuel-efficient platooning. Furthermore, it becomes evident that starting from the same node leads to an anyway lower amount of required daily rest periods, making larger savings even more difficult to be achieved. This can be explained by our limited network size which naturally bears shorter distances to be covered in the overall more centrally located instances of such a setting. Yet, figure 14 shows impressive pause time reductions.

Taking both the fuel- and wage-related implications of a 50% task relief into account, we can again identify notable percentage savings in comparison with the achieved total cost level of the basic EU-TPP. Figure 15 illustrates the resultant average net effects for each type of instances and problem size respectively.

On the one hand, we have seen in the above explanations that the incorporation of a task-relieving effect into the EU-TPP leads to rather ambiguous outcomes with regard to the PER and the associated fuel savings. On the other hand, it must be stated that a politically granted task relief will never result in a higher overall total cost level than none. So the entire platooning market would always be better off with its introduction. What the EU-TPP model then basically does is just providing more flexibility to the coordinating party by suggesting the financially more attractive alternative between either increasing the fuel economy further in a platoon or reducing the labor cost part of the TCO. In our experiments, the larger positive cost impact of the introduced task relief among these two options comes from its typical characteristic to reduce the amount of legally required breaks and daily rests. Consequently, the average values of the respective percentage total cost savings in figure 15 can be largely attributed to the generated personnel cost ones from figure 13. In essence, the course of the above graph and its underlying data thus reflect almost the same shape and characteristics. Therefore, we refer to the previous elaborations for a detailed explanation of the identified pattern from a task relief of 50%. Bearing in mind that the conventional EU-TPP has already generated substantial savings by merely relying on the fuel economy facet of platooning, the additional consideration of a task relief further enhances the potentials of this promising new technology to a whole new level of up to 14.67% in one case at maximum. Due to the limited network size which we based our experiments upon, it is expected that the relative additional total savings potential in a same-start setting would actually be even larger than indicated in figure 15.

The following table represents the resultant overall cost savings improvement of including a share of 50% task relief into the basic EU-TPP, based on the equivalent total cost levels of the standard planning model without platooning in the EU.

the potential task-relieving effects of platooning are considered in the exact EU-TPP. Large average improvements of up to 4.27% by contrast with disregarding a task relief clearly emphasize the economic attractiveness of less charged driving times for truckers in a trailing position within a platoon. Primarily referring to what is actually possible by using this promising transport concept, we highly recommend that politics takes such a positive side effect of platooning into serious consideration when deciding upon future legal directions in this regard.

Summing up our impact analysis with respect to the consideration of a task-relieving effect of

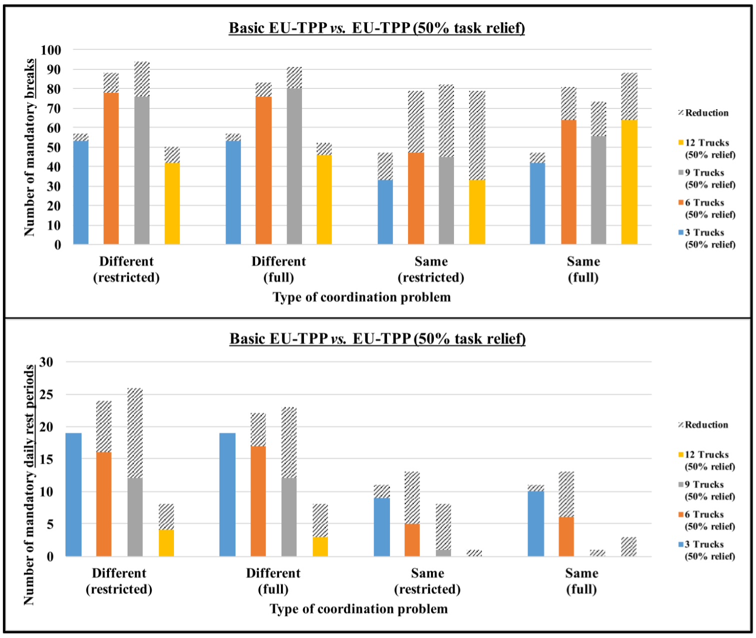

Figure 14: Reduction of mandatory breaks and daily rest periods

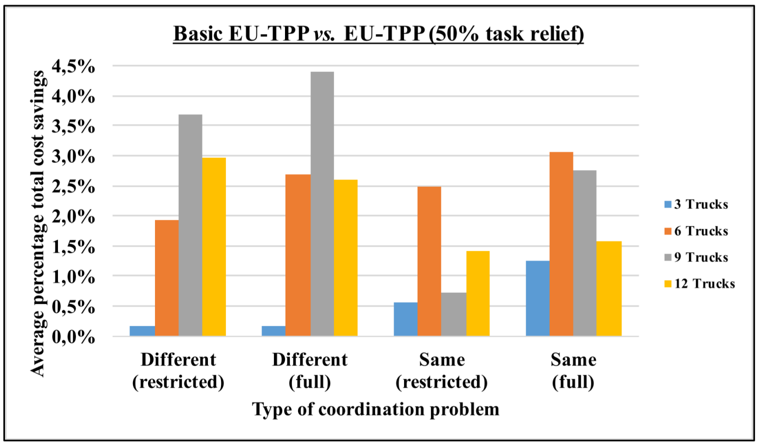

Figure 15: Average total cost savings under consideration of a 50% task relief

50% for PFs within the exact EU-TPP, we can conclude that:

. . . a granted task relief can lead to both more or less percentage fuel cost savings.

. . . literal ‘jumps’ in additional percentage personnel cost savings can be achieved by the sudden elimination of originally required daily rest periods.

. . . more restricted time windows are more likely to bear less wage-related savings.

. . . a certain threshold amount of trucks is required to effectively exploit the personnel cost savings potentials from platooning – which is easier to realize with a same-start coordination approach.

. . . the combined effect of fuel-related and personnel cost savings from platooning in a task-relieving manner leads to remarkable total cost savings on average.

. . . additionally scheduled waiting times due to eliminated mandatory pauses can actually reduce the wage-related effect of a task relief on the total cost structure as those natural chances to form platoons are suddenly missing.

. . . an amendment of Regulation (EC) No 561/2006 in matters of any task-relieving share from platooning would always lead to at least the same, but quite possibly a much larger amount of total cost savings as those created without its application.

Table 14: Impact of a 50% task relief on the total cost savings structure

Number of vehicles	Average percentage total cost savings	Different start (restricted)		Different start (full)		Same start (restricted)		Same start (full)	
		Average	Max	Average	Max	Average	Max	Average	Max
3 Trucks	EU-TPP	0.44%	2.93%	0.92%	3.51%	0.68%	3.48%	2.59%	5.52%
	EU-TPP (50%)	0.60%	4.17%	1.08%	4.17%	1.23%	14.75%	3.81%	16.04%
	Improvement	+0.16%	+1.71%	+0.16%	+1.71%	+0.55%	+12.33%	+1.22%	+12.76%
6 Trucks	EU-TPP	1.03%	3.11%	1.88%	4.24%	2.36%	4.33%	4.54%	5.77%
	EU-TPP (50%)	2.91%	11.58%	4.50%	16.83%	4.76%	14.27%	7.47%	19.11%
	Improvement	+1.88%	+9.60%	+2.62%	+13.89%	+2.40%	+11.51%	+2.93%	+13.90%
9 Trucks	EU-TPP	1.57%	2.95%	2.73%	4.07%	2.94%	4.50%	5.37%	6.47%
	EU-TPP (50%)	5.18%	13.36%	7.00%	17.04%	3.63%	11.23%	7.98%	17.38%
	Improvement	+3.61%	+12.30%	+4.27%	+13.87%	+0.69%	+8.63%	+2.61%	+13.03%
12 Trucks	EU-TPP	1.75%	3.56%	3.23%	4.55%	3.43%	4.55%	6.09%	6.99%
	EU-TPP (50%)	4.66%	11.66%	5.73%	12.72%	4.81%	13.08%	7.57%	11.14%
	Improvement	+2.91%	+10.18%	+2.50%	+9.94%	+1.38%	+10.10%	+1.48%	+5.98%

6.2. Performance evaluation of the heuristic solution approaches

The exact EU-TPP model delivers promising results in terms of actual savings potentials from platooning – be it from a fuel or personnel cost perspective. However, when it comes to computational efficiency, long processing times render its application less attractive. To this end, we evaluate the performance of our two approximate matheuristics by looking closer at their solution quality, before we contrast their average processing times with those of the exact EU platooning formulation then. A trade-off analysis between these two dimensions rounds off this section. But first, some basic observations are presented in advance.

6.2.1. General observations

Similar to subsection 6.1.1, table 15 summarizes some basic observations with regard to additionally scheduled waiting times (incl. more time-consuming split daily rest periods) and the solution process of our created instances by Xpress, depending on the problem types, the coordinated amount of trucks and the applied matheuristic model.

As becomes immediately visible, almost all instances of both the SPH and the PRH are solved to optimality, whereas none is left without any solution at all after the preset runtime limit of 3600 s. Only 2 out of 480 instances for the SPH and 3 out of 480 instances for the PRH are not completely finished yet, exhibiting an anyway negligible average optimality gap of up to 0.42%. The overall achieved solution maturity within that maximum possible time frame thus turns out to be very high for these two similar heuristic approaches. Their characteristic to divide the entire platoon coordination problem into a separate routing part (incl. decisions upon pause locations) and a subsequent scheduling part with the final platooning decisions makes it much easier for the optimization software to handle the present computational complexity. Apart from a few outlier values which can be primarily attributed to the still unsolved instances, the average processing times are generally on a low level. However, such a fast and stepwise approximation approach most probably comes at a cost in terms of solution quality. We will follow up on this in the subsequent subsection.

Where the average processing times are concerned, we can identify a remarkably high similarity between the SPH and the PRH, too. As both heuristics share the exact same step 2 in the hierarchical structure and only differ in their respective route priority (if at all) within step 1, the chosen decomposition approach naturally leads to a mostly similar computation process. The occurring temporal differences of the SPH's and the PRH's corresponding instances are rather negligible on average. So the additional search for generally existing platooning opportunities throughout the planning horizon in the PRH in contrast to the mere focus on a shortest path solution does not lead to significant drawbacks. Indeed, this could be well reasoned by the fact that the alternative platoon routing is mostly equivalent to the shortest path due to the inherent lack of detours in our limited road network. But we believe that the average processing times would still not differ substantially as the upstream routing part does not include any temporal dimension so far.

In accordance with the general observations for the basic EU-TPP, the coordination of more trucks unsurprisingly leads to longer processing times because of an increasing complexity of the problem. Coordinating HDVs from the same origin location seems to be computationally more expensive to some extent, whereas restricted time windows largely seem to result in lower average processing times than unrestricted ones on average. Since the route to take as well as the locations for mandatory idle times are already determined in the upstream step of both hierarchical approaches, the decision space is even more narrowed down in the restricted cases. This makes it a little easier for Xpress to find an optimal solution. Moreover, though, there is no logical explanation for

Table 15: Overview of general output statistics – part 2

Model	Type of coordination problem	Number of vehicles	Solved to optimality	No best solution found in time	(Sub-) Optimal solutions...	...with average optimality gap	Additional waiting time / rest steps (optimal)	Average processing time [seconds]
SPH	Different start (full)	3 Trucks	30	0	0	0.00%	0	19
		6 Trucks	30	0	0	0.00%	0	72
		9 Trucks	30	0	0	0.00%	0	155
		12 Trucks	30	0	0	0.00%	3	417
	Different start (restricted)	3 Trucks	30	0	0	0.00%	0	17
		6 Trucks	30	0	0	0.00%	4	63
		9 Trucks	30	0	0	0.00%	1	142
		12 Trucks	30	0	0	0.00%	4	215
	Same start (full)	3 Trucks	30	0	0	0.00%	0	25
		6 Trucks	30	0	0	0.00%	0	183
		9 Trucks	30	0	0	0.00%	3	290
		12 Trucks	28	0	2	0.42%	3	677
	Same start (restricted)	3 Trucks	30	0	0	0.00%	0	43
		6 Trucks	30	0	0	0.00%	0	101
		9 Trucks	30	0	0	0.00%	3	142
		12 Trucks	30	0	0	0.00%	3	236
PRH	Different start (full)	3 Trucks	30	0	0	0.00%	0	19
		6 Trucks	30	0	0	0.00%	0	74
		9 Trucks	30	0	0	0.00%	0	156
		12 Trucks	29	0	1	0.18%	3	507
	Different start (restricted)	3 Trucks	30	0	0	0.00%	0	17
		6 Trucks	30	0	0	0.00%	1	63
		9 Trucks	30	0	0	0.00%	4	142
		12 Trucks	30	0	0	0.00%	0	206
	Same start (full)	3 Trucks	30	0	0	0.00%	0	25
		6 Trucks	30	0	0	0.00%	0	183
		9 Trucks	30	0	0	0.00%	3	365
		12 Trucks	28	0	2	0.32%	0	668
	Same start (restricted)	3 Trucks	30	0	0	0.00%	0	42
		6 Trucks	30	0	0	0.00%	0	94
		9 Trucks	30	0	0	0.00%	3	150
		12 Trucks	30	0	0	0.00%	0	214

the longer same-start processing times other than the explicit underlying network constellation's influence along with the predetermined pause locations. We believe that this observation can therefore be neglected as different-start problems are normally expected to be of higher complexity (see subsection 6.1.1). We will further analyze the heuristics' respective average processing times in comparison with those of the exact EU-TPP formulation in more detail later.

As regards additionally scheduled waiting time steps for all instances that are solved to optimality, no particular pattern can be identified. This circumstance can be explained by the fact that the locations for mandatory breaks and daily rest periods are determined regardless of actually feasible platooning opportunities in step 1 of the matheuristics. Hence, extra waiting times might be more necessary in some rather unfavorable cases than in others, where the platooning trucks' required pauses are coincidentally planned at the same node anyway, for example. Especially a same-start setting with the fully available planning horizon would normally not exhibit any optional waiting times in the absence of a task relief at all, if mandatory idle times were scheduled jointly (see also subsection 6.1.1). The prior decision upon their locations makes it thus more difficult to interpret the optionally scheduled waiting times in step 2 from a logical perspective.

> Summing up our general observations based on the performed experiments for the introduced SPH and the PRH, we can conclude that:
>
> ...both matheuristic approaches exhibit an almost identical behavioral pattern in terms of the entire solution process because of their similar decomposed structure.
>
> ...both heuristics give a highly convincing impression with regard to the average processing times and the overall achieved solution maturity within the preset runtime limit of 3600 s due to

their decreased level of computational complexity.

6.2.2. Solution quality

Matheuristics like ours are usually characterized by combining the strengths of exact methods with a higher computational efficiency through the structural decomposition of a complex problem into smaller and easier to solve (sub)problems. Nevertheless, these approximate approaches lead to a resultant trade-off between the achievable solution quality and its correspondingly required processing time. In order to be able to perform such a trade-off analysis later on, we evaluate the solution quality of the SPH and the PRH first. For this purpose, figure 16 illustrates the achieved fuel cost savings of our matheuristics for each problem type and size as percentage shares of the maximum possible ones generated by the exact EU-TPP formulation accordingly. As only very few additional waiting times are scheduled, the average percentage increase of personnel cost can rather be neglected like in the investigations for the exact EU-TPP in subsection 6.1.2. Consequently, the structure of the average percentage total cost savings from our heuristics can again be almost fully attributed to the mere fuel-saving effect from platooning. We will thus not focus on these specific cost in more detail here – just as little as on the PER which behaves almost synchronously to the fuel savings. First of all, we can generally conclude from figure 16 that both matheuristics are able to generate remarkable fuel cost savings from platooning which are close to the optimum. A non-negligible fraction of instances is even solved to absolute optimality, particularly in the same-start coordination problems.

Some rather steep increases in the achieved share of maximum fuel cost savings further underpin our prior conclusion about the need of a certain network saturation level to effectively exploit the benefits of platooning. Especially doubling the problem size from 3 to 6 HDVs in the restricted cases seems to bring about large improvements. As regards the dashed average lines among all types of problems, it is unmistakably visible that an increasing number of coordinated trucks strengthens the solution quality further while flattening out. This becomes also apparent with the upward pattern in the boxplots' increasing minima as the problem size grows. One could even say that the more trucks are coordinated in the network, the higher are the chances to achieve (near-)optimal solutions as the boxplots are also consolidating and evening themselves out at a certain level. These findings are quite promising for a larger-scale application of our heuristic approaches and can be explained as follows:

In general, both the SPH and the PRH lack the possibility to jointly schedule mandatory breaks and daily rest periods for potential platooning partners because their location is already determined separately in the first hierarchical step. Apart from this, the two approximate approaches cannot rely on an increased flexibility in terms of break or rest period splitting like in the exact EU-TPP. As indicated in the previous subsection, such a strategy can lead to an unfavorable initial situation for the second step where less platoons could actually be formed in consequence then. Some required idle times might be planned too early and some too late on the route like this in order to be able to fully exploit the platooning concept at all.

Additionally, the trucks respective paths are not always effectively concerted for platooning purposes and only determined regardless of actually feasible convoy formations. Please be aware that the resultant variable computational behavior of our heuristics can also be responsible for some deviations from the originally expected graph courses in the above figure. The slight downturn in the SPH's unrestricted same-start graph when increasing the number of HDVs from 3 to 6 would be one such example. But usually, the impact of these inherent characteristics slowly disappears with more vehicles entering the system as new platooning opportunities emerge which could actually take advantage of such properties. In other words: it becomes more likely that other trucks will compensate the lack of jointly scheduled trips. The originally suspected downsides of our matheuristics are thereby virtually eliminated. Consequently, their solution quality is supposed to approximate the exact EU-TPP's optimal solution even more with an increasing amount of coordinated trucks.

Moreover, we can again identify the clear superiority of a same-start coordination approach towards a different-start one, while also recognizing the advantage of more flexible time windows for fuel-efficient platooning. As both the SPH and the PRH are largely based on the exact model formulation of the EU-TPP, its basic coordination principles relating to different types of problem instances apply here as well, despite the specific characteristics of our matheuristics. We thus refer to subsection 6.1.2 for a detailed explanation of these very similar observations.

Finally, we are also interested in actually existing performance differences between our two heuristic approaches with regard to the respectively achieved shares of maximum fuel cost savings. Overall higher located interquartile ranges of the PRH's boxplots indicate a slight relative advantage over the SPH. In order to have a closer look at the performance gap between the SPH and the PRH in terms of solution quality, figure 17 contrasts the average values per number of coordinated trucks in the network for each type of coordination problem.

As can be seen, the SPH turns out to be inferior in nearly all column comparisons on average. Even if the differences in the generated solution quality are not of an extreme extent in general, their occurrence in 14 out of the 16 visualized cases might suggest an unambiguous pattern. Nevertheless, it is difficult to derive a clear and undoubted superiority of the PRH for several reasons.

On the one hand, both approaches share the same specific features which we described above relating to the separate determination of the drivers' mandatory pauses and associated splitting rules. The only difference lies in the route choice along with possibly diverging pause locations which are sometimes more, sometimes less favorable for the coordination of platoons. On the other hand, our limited network size naturally leads to platoon routings which actually corre-

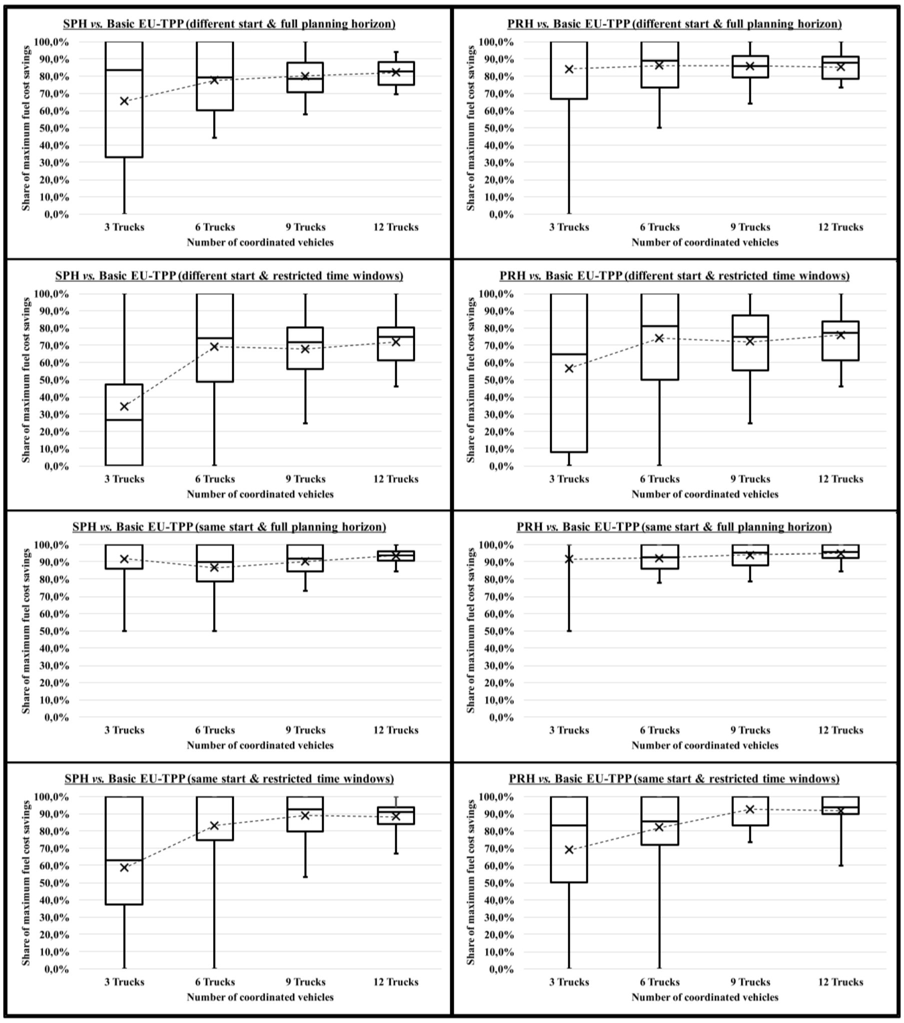

Figure 16: Relative solution quality for each type of coordination problem

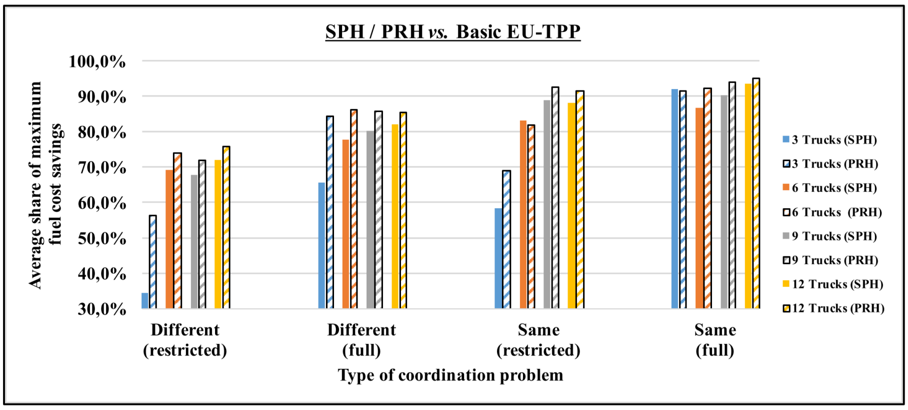

Figure 17: Differences in relative solution quality between matheuristics

spond to the shortest path in most cases. No longer, but only equally long detours on the central circle involving Munich, Salzburg, Verona and Venice (if at all) are possible due to the chosen equal edge lengths of 6 time steps. More extensive investigations based on larger networks with more route alternatives would be necessary to identify and evaluate a potential superiority of either heuristic approach.

The question is in general, if it is worth taking the risk of choosing the most frequented platooning path throughout the planning horizon which could eventually turn out to generate a lower PER than the normally used shortest path. In the end, diverging temporal constraints between the single trucks might result in misleading schedules with the PRH in real-world applications, but also bears the potential to increase the PER by taking a detour. The SPH might thus be more straightforward to use and more accepted by fleet managers. However, we believe that differences in the anyway convincing solution quality between the SPH and the PRH even themselves out with more vehicles to be coordinated in the network.

> Summing up our investigations about the fuel savings-related solution quality of our hierarchical planning-based SPH and PRH, we can conclude that:
>
> . . . both matheuristics generate highly promising, (near-)optimal solutions with regard to those obtained by the exact EU-TPP formulation.
>
> . . . their respective solution quality increases and stabilizes itself at a certain, close to optimal level with more trucks in the system to be coordinated on average.
>
> . . . both heuristic approaches are basically decomposed and simplified versions of the conventional EU-TPP and thus exhibit similar behavioral patterns with regard to different kinds of coordination problems.
>
> . . . no stepwise optimization approach is really superior to the other one.

6.2.3. Processing times

Exact methods are most accurate, but computationally expensive. After we have proven that our matheuristics provide highly convincing results in terms of solution quality, we will now focus on the required processing times within the preset runtime limit of 3600 s in order to derive conclusions about their computational efficiency compared to the exact EU-TPP model in the next subsection. To this end, figure 18 portrays the development of the average processing times per problem type as more trucks enter the platoon coordination system. Since we have already analyzed the respective processing time characteristics under certain types of coordination problems in subsections 6.1.1 and 6.2.1, we will not address these specifically here, but rather look into the interrelation between our models.

Please bear in mind that 82 out of 480 calculated instances of the EU-TPP and just 5 out of 960 computed instances for both heuristics together are still left unsolved to optimality after the given runtime limit. Hence, the basic EU-TPP would even display much larger average values than anyway.

Where the SPH and the PRH are concerned, we see almost congruent average processing time curves for the corresponding types of instances and the respective number of vehicles. As previously mentioned, this observation can be mainly attributed to the similar computational structure of both matheuristic approaches.

However, what stands out most is the flat, virtually linear course of their curves in comparison to those generated by the basic EU-TPP. Their rather exponential shape reflects the disproportionate increase in computational complexity as more trucks are coordinated by means of the most accurate platooning model. Indeed, the yellow and orange curves of both the SPH and the PRH already give a slight hint of a nonlinear growth of their average processing times – but to a considerably lower extent and primarily due to the aforementioned extreme outliers. Outsourcing the decisions upon the route choice as well as those upon the locations for mandatory breaks and daily rest periods from the main model thus turns out to have a highly favorable effect from a processing time perspective.

In order to further analyze and demonstrate the superior temporal performance of our two approximate approaches, figure 19 illustrates their achieved processing times within our experiments as shares of the EU-TPP's total processing times per instance type and problem size on average. Again, it needs to be pointed out that the graph below would even display a lower average level than anyway due to the many more instances of the exact model that have not been solved to optimality yet after the given runtime limit of 3600 s.

It becomes immediately apparent that both similarly behaving matheuristics can effectively display their inherent computational advantage when more vehicles are coordinated in our experiments. Apart from the suddenly rising yellow curves with 6 trucks, there is a clear positive downward trend visible among all types of instances. This observation can be reasoned by the much larger increase in the EU-TPP's computational complexity with a growing problem size. Such a characteristic seems quite promising for a larger-scale application of our heuristics where the processing times of the exact approach are expected to literally explode.

Nevertheless, it is worth mentioning that we can also identify a non-negligible number of instances, especially in the 3- and 6-truck cases, which exhibit longer processing times when being solved with either of the two hierarchical approaches. Table 16 shows the amount of such instances per problem type and size as well as the associated average temporal overhang in proportion to the EU-TPP's respective processing times.

To some extent, the longer processing times in some (particularly smaller) cases can be explained by the stepwise calculation property which makes it necessary to transfer the three former decision variables' values from step 1 as input parameters into step 2. The above described outlier values on both yellow curves originate from the 22 identified longer processing times out of 30. Yet, we cannot see an appropriate reason for the relatively large discrepancies in the same-start cases – with an up to even 686.93% longer processing time than the EU-TPP in a fully flexible 12-truck instance within the given runtime limit. The restricted different-start problem, for example, exhibits no such instances at all. But on the whole, their appearance decreases as more trucks enter

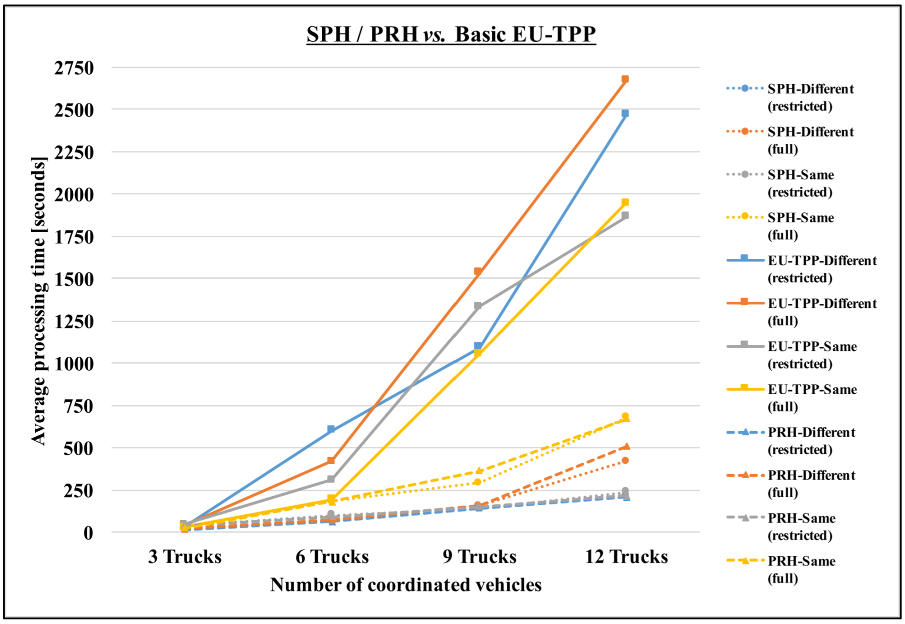

Figure 18: Development of average processing times in comparison

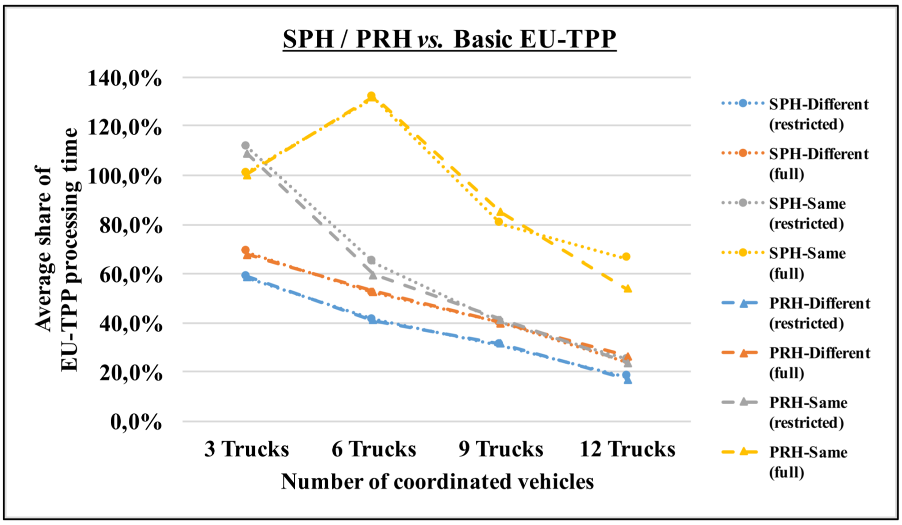

Figure 19: Relative processing time performance of matheuristics

the coordination system. This confirms our heuristics' temporal superiority towards the EU-TPP for even larger problem settings anew.

Please note that it was not possible to compute substantially larger instances with more vehicles, nodes and edges in the highway network due to the general computational complexity of coordinating truck platoons under consideration of mandatory driving time restrictions in the EU – neither with any of the two matheuristics, nor with the exact EU-TPP. Even if the processing times of the SPH and the PRH actually turn out to be much more promising for larger-scale applications, our computer's 16 GB working memory is still quickly depleted.

Summing up our processing time analysis for the SPH and the PRH in comparison with the exact EU-TPP formulation, we can conclude that:

> . . . both matheuristics clearly outperform the exact EU-TPP model in terms of processing time with a growing number of trucks to be coordinated in the system.

> . . . the two hierarchical planning-based approaches perform almost equally well as regards processing times, while exhibiting comparatively small rates of increase.

6.2.4. Trade-off analysis based on computational efficiency

After assessing both the overall generated solution quality in terms of fuel cost savings from platooning and the associ-

Table 16: Matheuristic instances with longer processing times

Type of coordination problem	Amount Time longer	SPH 3 Trucks	SPH 6 Trucks	SPH 9 Trucks	SPH 12 Trucks	PRH 3 Trucks	PRH 6 Trucks	PRH 9 Trucks	PRH 12 Trucks
Different start (full)	#	1	1	1	0	0	2	2	0
	Average	3.72%	7.86%	25.57%	0.00%	0.00%	1.01%	11.08%	0.00%
Different start (restricted)	#	0	0	0	0	0	0	0	0
	Average	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Same start (full)	#	18	22	5	1	16	22	7	3
	Average	18.40%	56.55%	150.62%	686.93%	20.90%	57.70%	118.04%	126.54%
Same start (restricted)	#	16	6	0	0	16	3	0	0
	Average	45.44%	28.25%	0.00%	0.00%	42.71%	19.48%	0.00%	0.00%

ated processing time behavior of our two matheuristics based on the ones of the exact EU-TPP formulation, it is now about time to contrast these key dimensions in a trade-off analysis. Our goal is to compare and evaluate their overall computational efficiency within the preset runtime limit of 3600 s. For this purpose, figure 20 delineates the three single models' average efficiency performance for the respectively coordinated amount of trucks across all types of coordination problems. Since the SPH and the PRH exhibited relatively similar behavioral patterns in comparison with the EU-TPP across all four instance types, we decided to provide one single average overview of their computational efficiency. Furthermore, same-start problems only represent special cases of different-start ones and time-windows will sometimes be more or less flexible in real-world applications anyway. Appendix H contains the individual representations. Instances with no best solution found in time have been completely excluded here.

Being in line with the conclusions drawn from the separate solution quality and processing time analysis, figure 20 clearly reveals the much higher computational efficiency of the SPH and the PRH for larger settings with more vehicles.

The exact model is still preferable for instances with 3 trucks due to the greater fuel savings at hardly any extra temporal effort. But its relative savings advantage shrinks rapidly with more vehicles coming into the network. This becomes best apparent when looking at the two extreme quadratic outliers for 9 and 12 trucks in the graph. While the average savings gap between the EU-TPP and the slightly worse performing heuristic of the two (i.e. the SPH) remains rather stable between around 0.5% and 1.0%, their average processing times diverge more and more. The reduction in computational complexity through a stepwise and slightly simplified optimization approach thus causes a rapidly increasing relative efficiency advantage and ultimately leads to highly satisfying results.

In the end, we can conclude that our hierarchical planning-based matheuristics largely outperform the EU-TPP in terms of computational efficiency, especially if a larger amount of trucks needs to be coordinated. Therefore, the SPH and the PRH finally turn out to be much more suitable for larger-scale applications where (near)optimal solutions should be found within a relatively short period of time.

6.3. Further qualitative sensitivity analyses

For computational memory and efficiency reasons, our numerical experiments have necessarily been carried out on a relatively small road network constellation with a limited number of nodes and trucks involved. Not least because of this, a specific and extensive quantitative analysis of some sensitivities has been disregarded so far. Only small observable effects, if at all, would have been the consequence. Nevertheless, the following subsections provide a qualitative discussion about some aspects which might essentially influence the decision to platoon. The respective implications are demonstrated by simple numerical examples in artificially modified settings. If not specified separately, all conventions regarding the road network and its parameters as described in subsection 5.1.1 apply.

6.3.1. Fuel-related and personnel cost aspects

Since fuel-related costs represent the major distance-dependent component of a truck's TCO, they are first and foremost the main driver to strive for efficiency-raising platoons at all. Our elaborations in the thesis at hand have been based on the assumption that all trucks are identical, thus feature the same fuel consumption behavior and face the same price level for Diesel and AdBlue. But also the fuel reduction factor enabled by platooning has been assumed to be equal among all trailing HDVs. More realistic scenarios would exhibit a large variety of different fuel-related characteristics though. And from a time-dependent perspective, the incidental personnel cost for the actually chosen manning options might differ among the vehicles' drivers as well, particularly when platoons are composed of trucks from different European countries with varying salary levels.

Unlike our assumptions in the numerical study before, such different circumstances might have a considerable impact on platooning decisions. These sensitivities are less relevant when trucks can already platoon from the same origin node just by smart scheduling. But they gain in importance as soon as HDVs have to merge somewhere in the network first – be it by smart routing with slight detours or decisions upon optional waiting times throughout the tour. Figure 21 illustrates a corresponding framework of trade-offs within the latter two formation strategies which are affected by the

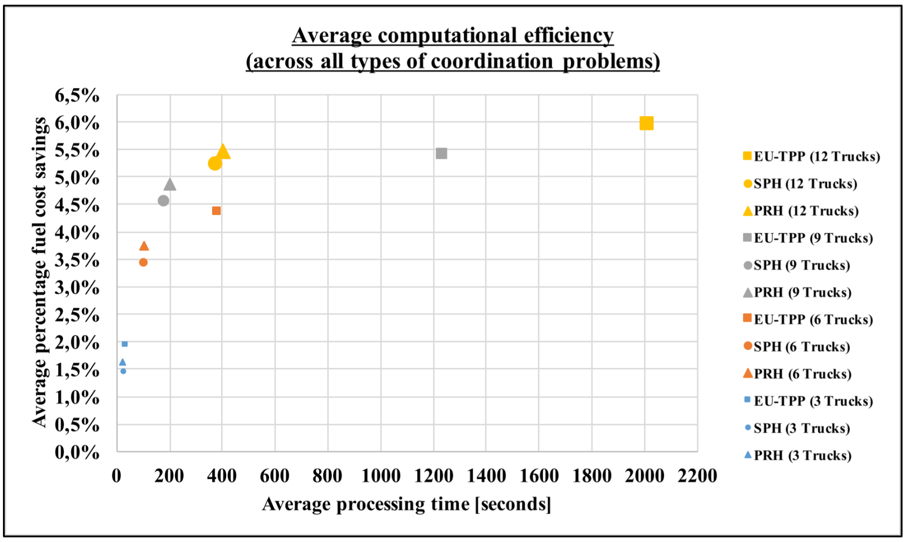

Figure 20: Trade-off between solution quality and temporal performance

actual magnitude of the aforementioned distance- and time-dependent cost influence factors.

In essence, the decision whether to accept a detour or to take an optional break is determined by contrasting the achievable fuel savings due to platooning with the additional expenses that need to be considered in return. While higher expenses on the time-dependent side will always decrease the chances to platoon in the absence of a task-relieving effect of trailing, the expected benefits from platooning might outweigh these and additional cost caused by increased distances. We have already taken advantage of such a distance-time (i.e. fuel-wages) trade-off in subsection 4.4.1, where an auxiliary constraint based on shortest paths for pruning purposes was introduced. Thus, the interrelation between distance- and time-dependent cost with their respective components is highly complex and sensitive.

As can be seen in the objective function (1) of the EU-TPP, the single fuel cost components are related to each other in a multiplicative manner. For this reason, we exemplify the distance-dependent sensitivity of platooning decisions based on the fuel reduction factor only. Now let us consider the scenario as presented in table 17, where time windows are restricted by extremely high lateness penalties of 1000 € . In order to examine the relevance of detours, the edge length between Munich and Salzburg is extended by 1 time step again. The effects of certain parameter variations on the respective courses of action are specifically demonstrated by trucks 1, 3 and 6. We first assume a uniform fuel reduction factor of 15% (like in our experiments), before we change it to 5%. Moreover, hourly wages are initially kept at 15 € and then we double the salary. Both manning options are allowed to demonstrate the interrelation between manning and platooning as a function of the fuel reduction factor and the salary level. The corresponding results, still without the consideration of a task relief, are given in table 18.

Unsurprisingly, a higher fuel reduction factor for convoys and lower hourly wages lead to increased overall cost savings. However, this cannot only be reasoned by the more favorable cost-influencing elements alone, but also by the increased readiness to make sacrifices which they induce for the sake of platooning.

In case of high wages and low expected benefits from trailing, only 6 edges are traversed in a slipstream-exploiting manner, whereby all involved trucks merged just by adequate departure time scheduling from the origin. Throughout the trip though, it is not worth the effort for trucks 1 and 3 to drive a detour or to wait voluntarily in order to profit from more platooning opportunities under such circumstances. The additional cost incurred would use up any financial benefits.

Where optional waiting is concerned, truck 3 only accepts one extra time step in Bologna to platoon with truck 5 to Perugia when at least the fuel reduction factor is increased or the personnel costs are halved. But as respects the willingness to consider a detour for utilizing the slipstream of a preceding HDV, the mere improvement of either wages or the platoon savings share is not sufficient. In addition to an extra time step for the longer route (like in the case of waiting), the distance-dependent costs also rise. This makes a detour less probable to occur than an optional waiting time unit.

For truck 6, double manning is generally the more cost-effective option to take without the presence of the platooning concept. The length of its route would necessitate at least one break and a costly daily rest period, which can be avoided by a team of two drivers in this special case. But as can be seen from table 18, new efficiency-raising platoons are formed by choosing to travel in a single-manned way as soon as the personnel cost and savings potentials are modified to the better. Despite the suspected advantage of circumventing mandatory pauses by double manning, actually exploiting these pauses as welcome possibilities to wait for each other in favor of an increased fuel economy with one driver

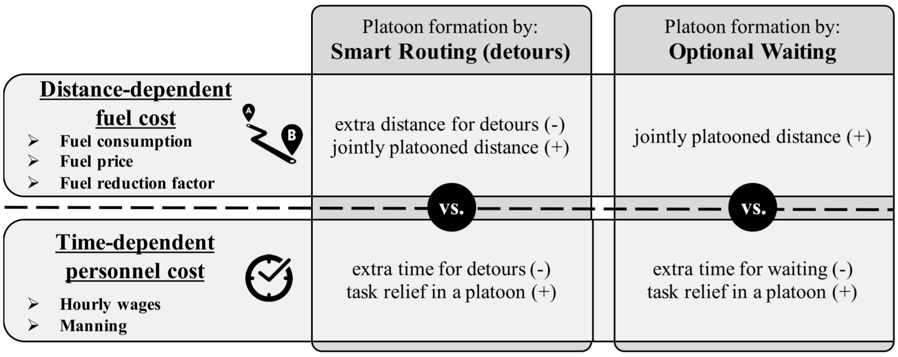

Figure 21: Relationship between different cost influencing factors and platoon formation strategies

Table 17: Sensitivity analysis – scenario 1: fuel and wages

Truck-ID	Origin	Destination	Earliest departure	Latest arrival	Effects of parameter variations on...
Truck 1	Innsbruck	Udine	0	30	detours (Truck 1)
Truck 2	Innsbruck	Salzburg	0	30	
Truck 3	Torino	Perugia	0	35	optional waiting (Truck 3)
Truck 4	Torino	Bologna	0	18	
Truck 5	Bologna	Perugia	22	35	
Truck 6	Rome	Innsbruck	0	100	manning (Truck 6)
Truck 7	Perugia	Venice	9	27	
Truck 8	Venice	Innsbruck	71	89	

Table 18: Results of sensitivity analysis – scenario 1: fuel and wages

#Platooned refers to the number of edges that have been traversed as a slipstream-exploiting follower in a platoon; (number) refers to a certain amount of time steps

		Fuel reduction factor (platooning)				Standard
		15%		5%		EU Model
Personnel cost per full hour	15 €	Total:	2044.38 € (-2.47%)	Total:	2082.72 € (-0.65%)	Total: 2096.25 €
		Fuel cost:	1181.88 € (-6.20%)	Fuel cost:	1242.72 € (-1.37%)	Fuel cost: 1260.00 €
		Wages:	862.50 € (+3.14%)	Wages:	840.00 € (+0.45%)	Wages: 836.25 €
		Truck 1:	detour	Truck 1:	no detour	
		Truck 3:	optional waiting (1)	Truck 3:	optional waiting (1)	Truck 6: double manning
		Truck 6:	single manning	Truck 6:	double manning	strictly shortest path
		#Platooned:	13	#Platooned:	8	no optional waiting
Personnel cost per full hour	30 €	Total:	2888.16 € (-1.51%)	Total:	2919.54 € (-0.44%)	Total: 2932.50 €
		Fuel cost:	1208.16 € (-4.11%)	Fuel cost:	1247.04 € (-1.03%)	Fuel cost: 1260.00 €
		Wages:	1680.00 € (+0.45%)	Wages:	1672.50 € (0%)	Wages: 1672.50 €
		Truck 1:	no detour	Truck 1:	no detour	
		Truck 3:	optional waiting (1)	Truck 3:	no optional waiting	Truck 6: double manning
		Truck 6:	double manning	Truck 6:	double manning	strictly shortest path
		#Platooned:	8	#Platooned:	6	no optional waiting

proves more attractive here. This clearly shows the close interrelation between the benefits of adequate manning and platooning decisions, thus emphasizing the need for further research in this regard. On a side note, it is worth mentioning that multi manning per se can be an obstacle for platooning, but also bears the potential to increase its benefits even further when being combined.

Summing up, we can conclude that a more favorable cost and savings structure additionally supports the formation of platoons. In three out of the four combinations, additional personnel costs occur which finally allow to save more fuel by the emergence of more actually realized trailing options in the end. At best, 2.47% of the total transport cost can be saved compared to the standard case without platooning – despite the higher salaries of even 3.14% that arise. However, the contribution of a 6.20% fuel reduction enabled by 13 slipstream-exploiting edge traversals repeals the prior disadvantage. Being heavily influenced by the variations of the single cost components, such sacrifices by optional waiting, detours or an initially implausible manning decision can consequently enhance, but also weaken the overall cost efficiency in a remarkable way.

6.3.2. Effects of hypothetical legal adaptation scenarios in the EU

We have already pointed out that there is a need for European politics to decide upon an amendment of mandatory driving time restrictions, if trailing in the slipstream is finally considered to require less attention. To this end, we want to qualitatively demonstrate the impact of different task-relieving shares by means of a short controlled numerical study with different start locations as well. While also referring to the 50% assumption of Tavasszy (2016), we take a closer look at the emerging contrasts when applying shares of 0%, 25%, 75% and 100% in a different-start setting subsequently[3]. These steps could be seen to resemble the hypothetical progress and degrees of maturity in platooning technology, where less driver alertness will gradually be required. As we have already shown the effects of certain fuel- and wage-related parameter variations on platooning, our goal is also to give some insights into their respective interrelation with a potential task-relieving effect. The scenario and its results for the single manning version of the exact EU-TPP, based on the same conventions as in the previous subsection, are shown in tables 19 and 20 respectively. Trucks 2 and 5 are chosen for demonstration purposes. Although double manning can exploit the impact of a task-relieving effect even more (see chapter 2), we still ignore team truck driving here due to the limited size of our network.

Of course, the extent of how much task relief is granted and to which financial conditions heavily influences the decision to platoon, as can be seen in table 20. At first glance, the only sub-scenario that involves higher wages than in the standard EU case without platooning is the basic one which we used in our extensive experiments in sections 6.1 and 6.2. Yet, without the presence of any task relief, it offers the highest percentage fuel cost savings with 3.76% – also leading to the highest total cost savings of 1.92% in this category due to an advantageous detour of truck 2 where the benefits of platooning can be exploited on two more edges.

While truck 5 is still legally forced to take a mandatory daily rest period with the full charge of driving time, any task relief of 25% and more makes such a costly pause completely redundant. This situation results in a tremendous jump in total, but particularly personnel cost savings. Suddenly, up to 25.15% of wage payments fall away. Indeed, the hypothetical share of 25% does not lead to more platooned edge traversals than before, the related fuel savings stay equal and even one extra waiting time step occurs for truck 5 in Bologna. Nevertheless, its impact is remarkable with slightly different platoons that are formed now to finally enable the exploitation of a task relief's potential.

Increasing its value to 50% – meaning that only half the driving time is actually charged as such – results in one platooned edge traversal more throughout all cases. Next to additional fuel savings generated from that, extra waiting time is not attractive anymore. Therefore, truck 5 joins another platoon configuration which fits better into its schedule and offers one more edge to be covered together. Overall, these changed conditions lead to a small, but further growth of the total cost efficiency.

While detours as a means to benefit from platooning have been too unprofitable so far except for the 15% / 15 € basic case, a hypothetical task-relieving share of 75% suddenly arranges for a new situation in all cases. Since truck 2 also has the possibility to follow in the slipstream of truck 1 along two additional edges when taking the slightly longer northern path from Innsbruck to Udine via Salzburg, it is now not obligated anymore to take a compulsory break of 3 time steps on this route. Therefore, the southern path with no platooning opportunities at all and the still existing break obligation turns out to be less advisable. Wage expenses are already reduced by 26.90% in this task relief category compared to the standard EU benchmark model, whereas the total transport cost keep decreasing as well.

However, the maximum savings from both a fuel and personnel cost perspective can be achieved with a task-relieving effect of 100%. Even if such a percentage does not seem realistic before fully automated trailing is enabled by major progresses in platooning technology at all, its implications are more than noteworthy. On the one hand, truck 5 does not have to take its mandatory break anymore because it can cover the major part of its route as a PF. Additional waiting time, which has been avoided so far, is scheduled instead in order to facilitate the formation of appropriate platoons. Hence, the salary level remains the same for three out of the four different cases when switching from 75% to a full remission of driving time. The only exception can be found in the bottom right corner with the most unfavorable cost and fuel-savings structure. A decrease of even 27.49% in personnel cost is possible here, but at the cost of two edges less that are traversed in a slipstream-exploiting manner compared to the other cases. This can be reasoned by the hourly wages of 30 € which make waiting less attractive when the fuel reduction factor of 5% is not very high either. The highest percentage savings in terms of fuel (5.99%) and overall transport cost (18.44%) are generated in the presence of high personnel cost and an efficiency-increasing factor of 15%.

Summarizing, we emphasize the importance of a careful political decision upon a potential task-relieving effect when

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[3] Please note that the variables $brClock_{v,i,m}$ and $drClock_{v,i,m}$ need to be defined as real instead of integer variables here, since the task-relieving shares along with the detour option can lead to fractional values – thus possibly leading to incorrect decisions. This transforms the ILP into a MILP.

Table 19: Sensitivity analysis – scenario 2: task relief

Truck-ID	Origin	Destination	Earliest departure	Latest arrival	Effects of parameter variations on...
Truck 1	Innsbruck	Salzburg	90	120	detours (Truck 2)
Truck 2	Innsbruck	Udine	90	120	
Truck 3	Rome	Bologna	0	18	optional waiting & pause shifting / elimination (Truck 5)
Truck 4	Bologna	Venice	20	26	
Truck 5	Rome	Salzburg	0	100	
Truck 6	Venice	Udine	26	32	
Truck 7	Udine	Villach	33	39	
Truck 8	Villach	Salzburg	39	45	

Table 20: Results of sensitivity analysis – scenario 2: task relief

#Platooned refers to the number of edges that have been traversed as a slipstream-exploiting follower in a platoon; (number) refers to a certain amount of time steps

		Fuel reduction factor (platooning) / Personnel cost per full hour			
		15% / 15 €	5% / 15 €	15% / 30 €	5% / 30 €
Standard EU Model		Total: 1512.45 € Fuel cost: 871.20 € Wages: 641.25 €		Total: 2153.70 € Fuel cost: 871.20 € Wages: 1282.50 €	
Hypothetical task-relieving share	0%	Total: 1483.44 € (-1.92%) Fuel cost: 838.44 € (-3.76%) Wages: 645.00 € (+0.59%) Truck 2: detour / break Truck 5: no waiting / break / daily rest period #Platooned: 6	Total: 1503.81 € (-0.57%) Fuel cost: 862.56 € (-0.99%) Wages: 641.25 € (0%) Truck 2: no detour / break Truck 5: no waiting / break / daily rest period #Platooned: 4	Total: 2127.78 € (-1.20%) Fuel cost: 845.28 € (-2.98%) Wages: 1282.50 € (0%) Truck 2: no detour / break Truck 5: no waiting / break / daily rest period #Platooned: 4	Total: 2145.06 € (-0.40%) Fuel cost: 862.56 € (-0.99%) Wages: 1282.50 € (0%) Truck 2: no detour / break Truck 5: no waiting / break / daily rest period #Platooned: 4
	25%	Total: 1322.19 € (-12.58%) Fuel cost: 838.44 € (-3.76%) Wages: 483.75 € (-24.56%) Truck 2: detour / break Truck 5: waiting (1) / break / no daily rest period #Platooned: 6	Total: 1342.56 € (-11.23%) Fuel cost: 862.56 € (-0.99%) Wages: 480.00 € (-25.15%) Truck 2: no detour / break Truck 5: waiting (1) / break / no daily rest period #Platooned: 4	Total: 1805.28 € (-16.18%) Fuel cost: 845.28 € (-2.98%) Wages: 960.00 € (-25.15%) Truck 2: no detour / break Truck 5: waiting (1) / break / no daily rest period #Platooned: 4	Total: 1822.56 € (-15.38%) Fuel cost: 862.56 € (-0.99%) Wages: 960.00 € (-25.15%) Truck 2: no detour / break Truck 5: waiting (1) / break / no daily rest period #Platooned: 4
	50%	Total: 1311.96 € (-13.26%) Fuel cost: 831.96 € (-4.50%) Wages: 480.00 € (-25.15%) Truck 2: detour / break Truck 5: no waiting / break / no daily rest period #Platooned: 7	Total: 1336.65 € (-11.62%) Fuel cost: 860.40 € (-1.24%) Wages: 476.25 € (-25.73%) Truck 2: no detour / break Truck 5: no waiting / break / no daily rest period #Platooned: 5	Total: 1791.30 € (-16.83%) Fuel cost: 838.80 € (-3.72%) Wages: 952.50 € (-25.73%) Truck 2: no detour / break Truck 5: no waiting / break / no daily rest period #Platooned: 5	Total: 1812.90 € (-15.82%) Fuel cost: 860.40 € (-1.24%) Wages: 952.50 € (-25.73%) Truck 2: no detour / break Truck 5: no waiting / break / no daily rest period #Platooned: 5
	75%	Total: 1300.71 € (-14.00%) Fuel cost: 831.96 € (-4.50%) Wages: 468.75 € (-26.90%) Truck 2: detour / no break Truck 5: no waiting / break / no daily rest period #Platooned: 7	Total: 1331.67 € (-11.95%) Fuel cost: 862.92 € (-0.95%) Wages: 468.75 € (-26.90%) Truck 2: detour / no break Truck 5: no waiting / break / no daily rest period #Platooned: 7	Total: 1769.46 € (-17.84%) Fuel cost: 831.96 € (-4.50%) Wages: 937.50 € (-26.90%) Truck 2: detour / no break Truck 5: no waiting / break / no daily rest period #Platooned: 7	Total: 1800.42 € (-16.40%) Fuel cost: 862.92 € (-0.95%) Wages: 937.50 € (-26.90%) Truck 2: detour / no break Truck 5: no waiting / break / no daily rest period #Platooned: 7
	100%	Total: 1287.75 € (-14.86%) Fuel cost: 819.00 € (-5.99%) Wages: 468.75 € (-26.90%) Truck 2: detour / no break Truck 5: waiting (3) / no break / no daily rest period #Platooned: 9	Total: 1327.35 € (-12.24%) Fuel cost: 858.60 € (-1.45%) Wages: 468.75 € (-26.90%) Truck 2: detour / no break Truck 5: waiting (3) / no break / no daily rest period #Platooned: 9	Total: 1756.50 € (-18.44%) Fuel cost: 819.00 € (-5.99%) Wages: 937.50 € (-26.90%) Truck 2: detour / no break Truck 5: waiting (3) / no break / no daily rest period #Platooned: 9	Total: 1792.92 € (-16.75%) Fuel cost: 862.92 € (-0.95%) Wages: 930.00 € (-27.49%) Truck 2: detour / no break Truck 5: waiting (2) / no break / no daily rest period #Platooned: 7

amending the legal framework for platooning. As can be seen in our controlled numerical elaborations, the corresponding labor cost savings can be significant when mandatory breaks and daily rest periods become no longer necessary. Irrespective of the salary level and the applied fuel reduction factor, results are more than convincing with longer distances that can be covered without the urgent necessity of a compulsory idle time. Along with a technologically appropriate amendment of the strict driving time regulations in the EU, the potentials entailed by platooning go far beyond the already attractive increases in fuel efficiency. A stepwise extension of the relieving share throughout the years of actual platoon application seems reasonable to this end. Anyway, the resultant increased flexibility allows for a highly cost-efficient design of transport tours – with potentially more platoons to be formed and less idle times to be scheduled. We thus recommend further quantitative investigations in the field of task relief based on larger networks, where trucks with different starts and destinations as well as different task-relieving shares can be considered.

6.3.3. Penalty cost for delayed deliveries

Missing deadlines of known customer time windows can be very costly and finally cause damage to a logistics service provider's reputation. For this reason, our previous elaborations have still assumed 'hard' time windows where no lateness is accepted at all. Nevertheless, it could be worthwhile to have a closer look at the trade-off between accepting a slight delay and taking the chance to increase fuel efficiency by platooning. This becomes even more important when stochastic travel times with unforeseen incidents are considered in the tour planning phase, which is part of future research. In order to derive corresponding financial implications from such 'soft' time windows where penalties occur in case of a delay, an artificial scenario based on the basic conventions of subsection 5.1.1 is presented in table 21. While the aspects of manning and task relief are ignored here, the edge between Munich and Salzburg is again extended by 1 time step to illustrate the occurrence of detours. Trucks 2 and 3 serve as test objects. The respective results are provided in table 22.

As can be seen, penalizing delays with high fines leads to less fuel savings in contrast with 'soft' time windows. The extra expenses for delays caused by additional waiting times or detours would outweigh the financial benefits of platooning in these 'expensive' cases.

Having a closer look at a penalty cost rate of 5 € though, it becomes evident that truck 3 suddenly takes a slight delay of 1 time step into account in order to form a convoy with truck 5 from Passau to Vienna. The supplementary fuel cost savings of 12.96 € , which are generated over two more platooned edges than before, clearly outbalance the additionally occurring cost of 5.00 € and 3.75 € for one unit of lateness and optional waiting respectively. Yet, truck 2 is still better off when avoiding to platoon over a longer route which would be associated with higher fuel cost, increased salaries and a still too costly delay.

However, as soon as only 1 € is charged for arriving at a customer location too late, new options emerge. On the one hand, truck 2 is now willing to consider a slight detour in favor of platooning. The penalty costs are almost negligible and the expected savings are higher than the related extra cost for fuel, personnel and lateness. Due to this decision, two more platooned edge traversals are possible – finally raising fuel savings to a level of 5.00% by contrast with the standard EU benchmark model. On the other hand, such a cheap penalty cost rate renders a delayed start and arrival of trucks 3 and 4 more cost-efficient than an optional waiting time of truck 3 in Passau. The platoon consisting of truck 3 and 5 still exists, but with the difference that it is facilitated by a later scheduled start of the former HDV now.

Despite the additional wages for detouring, the total cost savings of 2.41% in this special scenario represent about the triple of those generated in the presence of 'hard' time windows which we used for our extensive numerical experiments in sections 6.1 and 6.2. This finding suggests to further examine the influence of certain penalty cost levels on the required flexibility for platooning purposes in a larger network with more trucks. Moreover, the sensitivity analyses conducted before can be extended by a variable penalty cost component as well.

The next chapter will now address another interesting and important aspect which might heavily influence the coordination of platoons in the future: the mutual compensation between PFs and PLs.

7. Sharing the Benefits of Platooning

Our experiments have shown that the financial benefits of platooning can be considerable, even more when a certain saturation level of accordingly equipped trucks is reached after initial successes of this concept. Irrespective of the overall savings provided by platooning, the individually different profits of trailing vehicles would have to be shared with their corresponding leaders to keep the system running though. After all, PLs must have an incentive to be a leading truck without slipstream advantages at all. Profit allocation mechanisms could have a considerable impact on routing, scheduling and platooning decisions in the end. A slight detour might not be attractive anymore due to potentially higher compensation payments, for example. The opposite can be the case as well. To the best of our knowledge, there is no study addressing the topic of such mutual compensation schemes between PFs and PLs so far – neither theoretically nor practically. Therefore, we intend to provide a first basis for deeper investigations in this important subcategory of cost-efficient tour planning by using the concept of truck platooning. For this purpose, we briefly present a conceivable organizational framework first, before the next section actually gives an overview of some existing compensatory approaches from related fields of research in the literature. Afterwards, we aim to conceptually provide initial considerations about transferring and implementing these into a platooning-based transport environment.

7.1. Framework for a practical realization of mutual payments

The central question in this introductory section is how the allocation of generated savings by convoys could be systemically facilitated in practice throughout the different development stages of platooning at all. This issue is less urgent for platoons built by trucks belonging to the same fleet, but even more important for inter-organizational ones. One thing is clear: trust and information transparency are the key components for such a system to be successful.

Table 21: Sensitivity analysis – scenario 3: lateness penalties

Truck-ID	Origin	Destination	Earliest departure	Latest arrival	Effects of parameter variations on...
Truck 1	Innsbruck	Salzburg	0	13	detours (Truck 2)
Truck 2	Innsbruck	Udine	0	27	
Truck 3	Regensburg	Vienna	0	18	optional waiting / delayed start (Truck 3)
Truck 4	Regensburg	Passau	0	6	
Truck 5	Passau	Vienna	7	19	

Table 22: Results of sensitivity analysis – scenario 3: lateness penalties

#Platooned refers to the number of edges that have been traversed as a slipstream-exploiting follower in a platoon; (number) refers to a certain amount of time steps

		Penalty cost per delayed time step		Standard EU Model
		1 €	5 €	
Fuel reduction factor / (platooning) Personnel cost per full hour	15 % / 15 €	Total: 791.07 € (-2.41%) Fuel cost: 499.32 € (-5.00%) Wages: 288.75 € (+1.32%) Penalty cost: 3.00 € (3) Truck 2: detour / delay (1) Truck 3: no waiting, but delayed start & arrival (1) with truck 4 (1) #Platooned: 5	Total: 799.91 € (-1.32%) Fuel cost: 506.16 € (-3.70%) Wages: 288.75 € (+1.32%) Penalty cost: 5.00 € (1) Truck 2: no detour / no delay Truck 3: waiting (1) / delay (1) #Platooned: 3	Total: 810.60 € Fuel cost: 525.60 € Wages: 285.00 €
		Penalty cost per delayed time step		
		10 €	1000 € ('hard' time window)	
		Total: 804.12 € (-0.80%) Fuel cost: 519.12 € (-1.23%) Wages: 285.00 € (0%) Penalty cost: 0.00 € Truck 2: no detour / no delay Truck 3: no waiting #Platooned: 1	Total: 804.12 € (-0.80%) Fuel cost: 519.12 € (-1.23%) Wages: 285.00 € (0%) Penalty cost: 0.00 € Truck 2: no detour / no delay Truck 3: no waiting #Platooned: 1	

We have already referred to the role of a PSP for an ORP-based coordination approach in section 3.1.1. Hereby, a central service provider could "deal with administrative duties [. . .] and make sure that benefits of platooning are distributed fairly among the platooning partners" (Janssen et al., 2015). A shared database needs to be managed centrally to this end. However, such a neutral third party in the form of an official authority must also be financially covered by a lump sum, for example (see Besselink et al., 2016). Next to the cost aspect, it is furthermore not quite sure when exactly such a PSP will finally enter the market stage. Moreover, assuming that there is a distributed system of individual databases in the market – like it could be the case with an SOS-based approach without a neutral intermediary – the trustworthiness of shared information among the network participants can be questionable. This paves the way for another new promising technology called 'blockchains' which is suited to overcome aspects of trust and cost in return for probably higher implementation challenges.

Lindberg (2017) addresses the problem of how to organizationally realize mutual payments in a platooning environment based on the utilization of this decentral technology for transport issues in general. He concludes that neither a centralized nor a decentralized approach is explicitly superior towards the other. Historical data about past positions in a platoon would be important to balance the platooning benefits among the participating trucks over time. The reason is evident: "If network participants know that platooning benefits will be evenly distributed, the will to initiate and lead platoons is believed to be higher" (Lindberg, 2017). This is even more important as platooning partners might not necessarily cooperate in their daily business, but are rather competitors instead.

The following section gives some basic insights into how such a fair distribution of costs and profits could actually be achieved when collaborating horizontally.

7.2. Insights into basic compensation mechanisms

“Horizontal cooperation is about identifying and exploiting win-win situations among companies that are active at the same level of the supply chain in order to increase performance” (Cruijssen et al., 2007). And the concept of truck platooning creates such a setting, at least when appropriate benefit sharing schemes are available. As the incorporation of mutual compensation mechanisms into cost-efficient tour planning is not the major subject of this thesis though, we do not intend to provide an exhaustive overview of existing approaches. Such a review can be found in Guajardo and Rönnqvist (2016). Nonetheless, we would like to take the opportunity to present some common and practical mechanisms which could be interesting for future platooning-based applications. Since cooperative game theory “correctly assumes that collaboration will yield gains when compared to each company working individually, and focuses on how to create and divide these gains” (Vanovermeire and Sörensen, 2014), this field of research represents the ideal platform to search for appropriate solution approaches. The most essential and frequently applied ones are listed in table 23. While those marked in grey are LP-based models themselves and thus rather complicated, we subsequently concentrate on the first three concepts to get started with initial ideas for platooning.

For consistency reasons, we talk about the allocation of generated costs, although these approaches can be addressed from a mere savings or gain perspective, too. Let us define Y_p as the costs which are assigned to participant p if he collaborates with the members in a coalition Z. His stand-alone cost of working individually are denoted by $C(\{p\})$, whereas the jointly achieved cost of the coalition are indicated by C(Z). The most straightforward and comprehensible concept is probably that of Weighted Cost (WC). Here, the resultant total costs of a coalition are distributed proportionally to the respective participant’s individual cost in relation to the sum of all individual expenses before any collaboration. In principle, such a weighting can be done by means of other measures in different logistics contexts as well (e.g. purchasing volumes). Since platooning is primarily about the retrenchment of fuel expenses though, a cost-based weight seems most adequate. The cost allocated to a player p by this scheme is equal to

$$Y_p = \frac{C(\{p\})}{\sum_{p\in Z} C(\{p\})} * C(Z). \tag{68}$$

For an explanation of the widely used Shapley Value (SV), we additionally introduce S, representing one of many possible sub-coalitions within the grand coalition C(Z). This concept is a little more of theoretical nature, but its superiority in diverse settings has been proven by many publications so far (see table 23). Let us assume that any coalition is formed by sequentially entering participants, one after another. As soon as a single member enters a coalition, the total cost of that coalition increases while his marginal cost contribution to the corresponding coalition is assigned to him. In other words: considering every imaginable (sub)coalition, the value of the coalition without that player is deducted from the value of the new coalition including him. Therefore, the entering order essentially determines the amount which is allocated to this member. The SV just represents the average of all these marginal contributions and can be calculated as follows ($|*|$ stands for the number of players in the respective coalition):

$$Y_p = \sum_{S\subseteq Z\setminus p} \frac{(|Z|-|S|-1)! * |S|!}{|Z|!} * (C(S\cup p) - C(S)) \tag{69}$$

Where the next approach of Separable and Non-Separable Cost (SNSC) is concerned, we need to additionally define the marginal cost M_p of participant p and a weight W_p which is required for one of the two presented alternatives to allocate the non-separable cost G_Z of coalition Z. The underlying idea of this method is to charge each player by his separable (i.e. marginal) cost first, before distributing the remaining part of the overall generated expenses based on given weights.

$$M_p = C(Z) - C(Z\setminus\{p\}) \tag{70}$$

After calculating the marginal cost M_p for each participant, the non-separable share G_Z can be computed by subtracting the sum of all marginal costs from those of the grand coalition C(Z) in the next formula.

$$G_Z = C(Z) - \sum_{p\in Z} M_p \tag{71}$$

$$Y_p = M_p + G_Z * \frac{W_p}{\sum_{p\in Z} W_p} \tag{72}$$

The final calculation of the actually allocated cost Y_p for player p is dependent on the chosen weighting strategy in equation (72). On the one hand, the non-separable cost G_Z can be split equally according to the Equal Charge Method (ECM). On the other hand, the Alternative Cost Avoided Method (ACAM) distributes these costs based on the weight W_p. This value from equation (73) can be interpreted as the individual benefit of joining the grand coalition compared to the situation of operating alone.

$$W_p = C(\{p\}) - M_p \tag{73}$$

While these aforementioned cost or benefit sharing mechanisms are rather generic frameworks that can fit to a variety of application areas, we also want to introduce and suggest a more platooning-specific, but still very simple approach: the Hypothetical Cost of Trailing (HCT) scheme. As the name already implies, the central idea here is to assume that each truck p might hypothetically be a trailing one and thus benefits at least from a reduced fuel cost rate F_p. Similar to the

Table 23: Sensitivity analysis – scenario 3: lateness penalties

Compensation mechanism	Basic principle	Publications
Weighted Cost (WC)	Allocation of the totally generated costs / savings among the collaborating parties according to a weighted cost measure (e.g. stand-alone cost ratio)	D'Amours and Rönnqvist (2010), Frisk et al. (2010), Liu et al. (2010), Shoubi et al. (2013), Vanovermeire and Sörensen (2014)
Shapley Value (SV)	Allocation of the totally generated costs / savings among the collaborating parties according to the weighted average of each individual's marginal contribution to any possible coalition which can be formed (underlying assumption: parties are added to the coalition in a sequential manner and provide a certain positive or negative value respectively)	Cruijssen et al. (2010), Dahlberg et al. (2019), D'Amours and Rönnqvist (2010), Frisk et al. (2010), Krajewska et al. (2008), Liu et al. (2010), Lozano et al. (2013), Özener and Ergun (2008), Shapely (1953), Shoubi et al. (2013), Vanovermeire and Sörensen (2014), Vanovermeire et al. (2014)
Separable & Non-Separable Cost (SNSC)	Allocation of the totoally generated costs among all collaborating parties according to: – Separable Cost: marginal Cost of each player with respect to the Cost of all collaborating parties – Non-Separable Cost: remaining share of totally generated Cost Distribution of Non-Separable Cost possible in two ways: 1) Equal Charge Method (ECM): equal allocation 2) Alternative Cost Avoided Method (ACAM): weight, expressed as individual savings when joining the collaborating parties instead of operating alone	Audy et al. (2011), D'Amours and Rönnqvist (2010), Frisk et al. (2010), Shoubi et al. (2013), Tijs and Driessen (1986), Vanovermeire and Sörensen (2014)
Equal Profit Method (EPM)	Allocation of the toally generated savings among the collaborating parties such that the maximum difference in pariwise relative savings is minimized	Audy et al. (2011), Dahlberg et al. (2019), D'Amours and Rönnqvist (2010), Frisk et al. (2010)
Nucleolus (NC)	Allocation of the totally generated costs / savings among the collaborating parties such that the maximum costs / minimum savings of any coalition get minimized / maximized	Dahlberg et al. (2019), Frisk et al. (2010), Liu et al. (2010), Lozano et al. (2013), Özener and Ergun (2008), Schmeidler (1969), Shoubi et al. (2013), Vanovermeire and Sörensen (2014)

ECM version of the SNSC mechanism, the difference between the grand coalition's total cost and the sum of the individual PF-like fuel cost rates, denoted by R_Z, is shared equally among the participants. These two cost fractions are then added up to receive the respective players' allocated costs Y_p.

$$R_Z = C(Z) - \sum_{p \in Z} F_p \tag{74}$$

$$Y_p = F_p + \frac{R_Z}{|Z|} \tag{75}$$

Since the whole coordination process of platooning itself is highly complex anyway, a lot of factors need to be taken into account when deciding upon an appropriate compensation system for trucks in such an environment. The next section demonstrates how the above presented benefit or cost sharing mechanisms can quantitatively affect the individual cost structures of platooning trucks based on a simple scenario and qualitatively addresses some restricting factors.

7.3. Conceptual application for platoons and related discussion

Let us assume that 3 trucks are meant to form a fuel-efficient platoon at the same time, hypothetically profiting from a 10% lower fuel consumption when being assigned a follower's position in that closed system. We consider trucks at blanket cost rates with both the same and different fuel consumption behaviors separately. In this latter case, trucks are advised to merge according to the convention that the vehicle with the lowest fuel consumption always takes the leading position. The highest savings can be generated from a mere fuel perspective in doing so. Our EU-TPP approach as well as both matheuristics allow to take such a convention into account if lower vehicle indices are assigned to the more fuel-efficient HDVs before. Figure 22 shows the results when applying the different cost allocation mechanisms in theory. Please see Appendix A for a reference to the calculations.

Unsurprisingly, the final cost allocation is not influenced by the chosen compensation mechanism at all if the truck types are identical and exhibit the same fuel consumption behavior. Any weight or marginal contribution would always be the same, which makes such a rather idealistic setting much easier to handle.

However, subsection 6.3.1 has already pointed to the possible implications that differing fuel consumption behaviors can actually have for routing and scheduling decisions when considering the exploitation of slipstream effects. As we can see, unequal truck types reveal the characteristic differences between the single cost sharing approaches to a similar extent. Considering the underlying assumptions regarding the sequence of trucks within a platoon, the less perspicuous and more theoretical schemes like the SV or the SNSC seem to favor the leading vehicles more. The simpler and more intuitive mechanisms like the WC or the newly introduced HCT approach, on the other hand, impose a comparatively higher cost share on the leader.

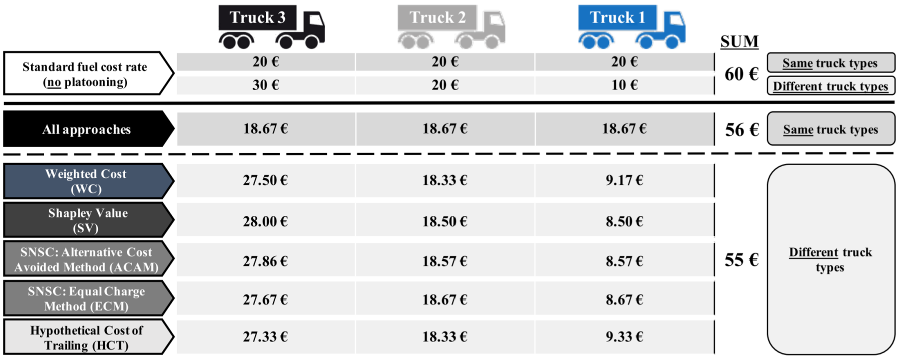
Even if the differences might be insignificant across the various allocations at first glance, the effect adds up and bears the potential to create resentment among some market participants. It is important to find the right balance between giving an incentive to lead and arranging for broad acceptance because "practical cases have shown that practitioners often regard the problem of constructing a fair gain sharing mechanism as too difficult or academic" (Cruijssen et al., 2010). In principle, no one is worse off when leading a platoon compared to a market without platooning opportunities at all. But especially during the early phases of platooning, its benefits must be available to all players in the market – not only to the followers – to reach a certain market saturation. Consequently, an adequately chosen compensation mechanism among the members of a formed platoon is of particular importance for the success of this new transport technology.

Nevertheless, building such a platoon is not just about the consideration of fuel effects. And it might be more suitable to choose another convention for the distribution of roles in a platoon than we did. Future research must also bear in mind that potential adaptations to European transport policies regarding driving times might heavily influence the sequencing decision within a platoon. A task-relieving effect when trailing might suddenly be more beneficial to exploit than an increased fuel economy. And frequent position changes might also appear to be necessary to enhance the saving potentials of platooning. Additionally, not all of the trailing trucks profit from the slipstream effect in the same way. Hence, the order of trucks within a convoy is not only heavily dependent on fuel aspects, but also on the impact of personnel cost and mandatory driving time restrictions, as well as on the current and past positions in a platoon. A mere index-based arrangement of trucks like with either our models might not be sufficient anymore in order to determine PLs and PFs. However, the introduced driver status variables may help in this regard. Furthermore, new status variables signaling the already held positions in a platoon could support with finding a system-wide optimal solution. But as new platoon-influencing factors are implemented into the EU-TPP, its already high computational complexity will most likely rise even further. Since the costs to be allocated also require frequent recalculations as more trucks join and leave a platoon in a dynamic real-world setting, additional complexity is incurred. This complexity is again fortified by surrounding possibilities to platoon, which might be more attractive from an individual point of view, but less favorable for the achievement of a system-wide optimum. As can be seen in this discussion, the issue of mutual compensation brings a whole new dimension of challenges to the coordination of train-like convoys.

But no matter which benefit sharing strategy will make it to an everyday application in a platooning-based transport sector: the chosen compensation mechanism must fulfill a lot of requirements. It needs to be sustainable, reliable, accepted among all the participating parties, both collectively and individually desirable, flexible, intuitive and easy to implement. The last aspect is even more important when it comes to an extension of our EU-TPP modeling approach which is anyway hard to solve to optimality. But first and foremost, fairness is the key to its success. Summing up, there are a lot of criteria that need to be discussed in this regard. Our first insights into the field of mutual compensations for fuel savings generated by truck platooning, together with the provided literature references in the previous section, can serve as a starting point for such further investigations.

8. Conclusion and Future Work

After gaining valuable insights into the cost-efficient coordination of platoons in the EU, it is now about time to provide a conclusion of our entire research process along with its major findings. We will then complete this thesis with a broad



	Truck 3	Truck 2	Truck 1	SUM	
Standard fuel cost rate (no platooning)	20 € 30 €	20 € 20 €	20 € 10 €	60 €	Same truck types Different truck types
All approaches	18.67 €	18.67 €	18.67 €	56 €	Same truck types
Weighted Cost (WC)	27.50 €	18.33 €	9.17 €	55 €	Different truck types
Shapley Value (SV)	28.00 €	18.50 €	8.50 €		
SNSC: Alternative Cost Avoided Method (ACAM)	27.86 €	18.57 €	8.57 €		
SNSC: Equal Charge Method (ECM)	27.67 €	18.67 €	8.67 €		
Hypothetical Cost of Trailing (HCT)	27.33 €	18.33 €	9.33 €		

Figure 22: Applied cost allocation mechanisms for truck platooning

outlook on future research directions in the field of truck platooning.

8.1. Conclusion

The aim of this thesis was to address some critical research questions relating to the actual application of the promising new concept of truck platooning in the EU due to its high political and economic relevance. Even if the standard problem of designing and scheduling cost-efficient tours under consideration of mandatory driving time restrictions increases further in complexity with the exploitation of this emerging transport technology, its remarkable fuel and personnel cost savings potentials justify larger efforts.

8.1.1. Systematic procedure and associated findings

First of all, it was necessary to efficiently extend the combinatorial problem of truck routing and driver scheduling by the financially attractive option to platoon under mandatory service time restrictions in the EU.

After presenting the major European legislation on road transport in chapter 2, we gained some insights into the field of truck driver scheduling and comprehensively reviewed the current status of platooning-related literature and research in chapter 3 in order to derive useful findings and ideas for an appropriate coordination approach. Based on this state of knowledge, we formulated the exact EU-TPP as an ILP in section 4.1 which primarily uses a joint routing and scheduling strategy to form and dissolve platoons before departure instead of speed adjustment maneuvers during the trip. Like this, our model lays the foundation for both SOS and ORP which we consider much more appropriate than a mere OTFP approach, especially in the early stages of platooning with relatively few platoon-ready vehicles in the network. Next to the opportunity to platoon, it comprises mandatory breaks and daily rest periods in the EU, their respective splitting rules and a hypothetical task-relieving effect for trailing in the slipstream of a preceding truck as special features.

In order to tackle the issue of computational complexity, we introduced two hierarchical planning-based matheuristics in section 4.2 which separate the mere routing decisions (incl. pause locations and manning) from those upon scheduling and platooning: the SPH and the PRH. These simplified solution approaches take advantage of the basic EU-TPP formulation and differ mainly in their route preference. Additionally, we implemented an auxiliary constraint based on maximally plausible and feasible detours for the sake of platooning to efficiently prune the generation of binary route variables in section 4.4.

Assuming a planning horizon of 30 h and a fuel reduction potential of 15% for PFs in a recreated graph of the European highway network between Germany, Austria and Italy with 22 nodes and 24 edges, we made the necessary preparations for our numerical investigations and validated the essential operating principles of our models after implementing them into Xpress by FICO. In doing so within chapter 5, we also proved the positive efficiency-raising effect of the aforementioned constraint. Its application in future research is thus highly advisable.

Resting upon the previous achievements, we conducted extensive quantitative experiments in sections 6.1 and 6.2 relating to different influence factors on and implications from the coordination of truck platoons in the EU in order to address the major research questions (ii) to (v). This was additionally supplemented by analyzing some specific sensitivities in a qualitative manner in section 6.3 then.

Where the performance of our exact EU-TPP approach is concerned, remarkable findings could be acquired with 3, 6, 9 and 12 trucks to be coordinated at a time. Although the computational complexity rose drastically with an increasing amount of HDVs, fuel cost savings of up to 9.33% for the same-start settings and 5.59% for the different-start ones were achieved on average without a task relief for followers in a platoon. Indeed, its consideration to the amount of 50% led to rather variable fuel cost changes, but could improve the total cost structure tremendously by up to 13.90% from originally 5.21% in one unrestricted same-start case with 6 trucks. Mandatory breaks and daily rest periods that suddenly became no longer necessary arranged for personnel cost savings of up to 31.86% at best, being able to take the benefits of truck platooning to a whole new level.

Contrary to prior expectations, the impeding character of compulsory driving time restrictions on platooning proved to be rather small in our experiments. In fact, these prescribed pauses turned out to represent real and natural chances for the formation of platoons. We could underpin this conclusion with the larger amount of optional waiting times that were additionally scheduled with a 50% task relief. Therefore, we conclude that a joint optimization approach like ours is actually able to take advantage of binding EU law for the sake of platooning.

While more restricted time windows resulted less favorable for platooning due to the lack of temporal flexibility for scheduling purposes, increasing the number of coordinated vehicles had a highly promotional effect on the savings structure. Our investigations also emphasized the importance of a certain threshold amount of trucks in the coordination system to effectively exploit the benefits of platooning – be it from a fuel or personnel cost perspective. Such a higher saturation level is automatically available when trucks are coordinated from the same origin node.

The favorable and inherent local preconditions of a same-start coordination approach make it possible to focus more on the scheduling part of platooning, ultimately resulting in larger savings and shorter processing times on average. Routing, scheduling and finally platooning trucks from and to widely dispersed locations implies a higher computational complexity along with fewer edges that can actually be traversed in a slipstream-exploiting manner overall.

As regards our promising matheuristics based on either the strictly shortest path (SPH) or the most frequented platooning path throughout the planning horizon (PRH), we could present highly convincing and almost congruent results in terms of the achieved solution quality and required processing times. The average shares of the maximum achieved fuel cost savings from the EU-TPP ranged between 67.62% and 86.10% for the different-start, and between 81.86% and 95.04% for the same-start problems after an apparent threshold of 6 trucks was reached. Many instance runs even led to the exact optimal solutions. We concluded that the coordination of a larger amount of vehicles also strengthens the achievable solution quality of our approximate heuristics, even more when sharing the same origins.

This circumstance is well in line with their processing time behavior. While the EU-TPP exhibits an exponentially growing computational complexity with more trucks entering the system, we experienced much more smoothly increasing average processing times of the SPH and the PRH. Consequently, a trade-off analysis contrasting the two dimensions of solution quality and processing time resulted in a high computational efficiency advantage of our matheuristics compared to the exact EU-TPP model for larger problem sizes.

Furthermore, we showed in a qualitative sensitivity analysis based on an artificially controlled setting that factors like manning, the chosen share of a task relief for PFs, wage levels, fuel consumption-related aspects and penalty cost for delayed arrivals at the destination can have a considerable influence on platooning decisions – not least due to their interrelation with decisions upon detours or optional waiting times. Hence, the entire platooning framework proves to be very fragile.

In addition, some conceivable cost and benefit sharing mechanisms were introduced and discussed based on a review of related research in chapter 7 to specifically identify suitable approaches for a platooning-based transport environment. We believe that appropriate and fair mutual compensation strategies among the collaborating members of a platoon are indispensable as the actually non-profiting PL must have an incentive to lead a convoy at all. The successes of platooning thus also depend on future elaborations in this direction. We provided a first basis.

8.1.2. Major recommendations for action

As the early stages after the market introduction of truck platooning will be characterized by relatively few accordingly equipped trucks, we initially recommend a mere same-start coordination approach based on SOS – at least as far as possible – until a certain network saturation allows for the transition into an integrated different-start strategy. On the one hand, the generally identified much higher savings level when relying on the more favorable local preconditions is expected to convince more and more fleet managers of the platooning concept. And on the other hand, the processing times are also expected to be lower according to our research results. Basically, the same-start problem is just an easier to solve variant of the different-start problem where it is possible to focus more on the scheduling part of platooning. In the course of time, advances in computing power could slowly pave the way from such a hub strategy to the coordination of HDVs from dispersed locations throughout the road network, managed by a neutral PSP.

Moreover, we highly advise European politics to delve into the topic of a potentially granted task relief for followers in a platoon. Apart from the enormous personnel cost savings potentials that we proved to appear with a ‘discount’ on driving times of 50% within our experiments, the actually defined task-relieving percentage is expected to have a considerable impact on the total cost structure as we have shown in our qualitative analysis. An amendment of Regulation (EC) No 561/2006 is thus urgently required as it would significantly increase the entire transport sector’s efficiency in any case.

Finally, we recommend to apply the exact EU-TPP model for small platoon coordination tasks, whereas the SPH should be the preferred approach for dealing with a larger number of vehicles. Even if the PRH performed slightly better by chance than the SPH during our investigations, we suggest that it is not worth making a potentially misleading platooning decision. Truck drivers would anyway take the shortest path from their origin to the respective destination in most cases, leading to a higher acceptance of the SPH among fleet managers in the end.

8.1.3. Critical reflection

After all, it must be pointed out that the limited size and shape of our utilized road network as well as the relatively small amount of coordinated trucks restricted us in deriving concrete implications for larger real-world instances. Closely linked with that is the inherent lack of actually feasible detours to gain some closer insights into the difference between the SPH and the PRH. This fact can simply be traced back to the high computational complexity of the EU-TPP which we were only able to face with limited computing capacities. Nevertheless, we believe that the ratio between the quantity of trucks and the network size was well-suited to draw sound conclusions on truck platooning in the EU anyway.

In fact, our matheuristics were not able to solve larger-scale instances with more trucks in the network than the EU-TPP due to the still quickly depleted working memory of 16 GB. However, their processing times actually turned out to be much more appropriate for such an application, not least because of the still lacking consideration of task reliefs and splitting rules for breaks and daily rests.

All in all, we could demonstrate that truck platooning has the potential to bring about remarkable fuel and personnel cost savings and finally made our contribution to turn it into an everyday reality for cost-efficient road transport in the EU. But there is still much work to do in the close future that we want to address now.

8.2. Future work

Without doubt, exploiting the concept of truck platooning for more cost-efficient transportation flows bears enormous potentials for the entire logistics sector. However, “there is a significant risk that the technology will never take off” (Verheyen, 2017) due to a possible reluctance of many carriers to pioneer in its exploitation for reasons of competition, uncertain legislative actions, unreliable coordination and risky business cases. Therefore, more persuasive research effort is required to prove feasible concepts and frameworks for the implementation of platooning. Based on the findings of this thesis as well as on our insights into the current state of platoon coordination literature, we decided to dedicate a separate section to future directions of research that inevitably call for further attention.

So far, all existing publications in platoon coordination literature only focused on simple one-way trips from an origin to a truck’s respective destination to ‘walk the first steps’ in this new field of research. Our contribution was to extend this framework by imposing mandatory EU driving time restrictions on this route in order to investigate their implications for platooning – be it in the presence of a hypothetical task relief for PFs or not. One of the next steps would be to transfer these considerations into a VRPTW-based context, i.e. solve the already complex VRPTW by simultaneously considering another NP-hard problem.

From a legal perspective, the actual surplus value of applying splitting rules for mandatory breaks or daily rest periods could be examined. But also the implications of incorporating more optional rules like extended driving times or reduced rest periods according to Regulation (EC) No 561/2006 should be assessed. Even if these options cannot be applied on a regular basis, they allow for more flexibility and could thus actually increase the chances to find compatible platooning partners. Particularly longer planning horizons for a VRPTW-type problem setting would be an appropriate platform for these rules to be investigated.

Herein, the inclusion of the whole set of mandatory legislative restrictions in terms of both driving and working hours (i.e. Directive 2002/15/EC) would further contribute to gather more insights into real-world applications. As more customer time windows need to be considered along with forced waiting times and defined slots for (un)loading at the respective customer locations in such a multi-stop context, the challenge of platooning gets even more complicated in the presence of restrictive service time regulations.

Anticipating legal adaptations with regard to a task relieving-effect for trailing in the slipstream of a preceding truck, it is also the last-mentioned directive apart from Regulation (EC) No 561/2006 that requires further attention. If driving in a following truck is associated with a reduced required alertness, politics needs to find answers to the question of how to legally handle potentially conducted administrative work during that time. Suddenly, the activities of driving and working are intertwined – making the decision about a modified legal transport framework for platooning even more complex. Our inclusion of a certain predefined factor for actually charged driving time in the exact EU-TPP represents an ideal starting point to assess the financial implications of conceivable legal adaptation scenarios in more detail. Nevertheless, larger instances with more nodes and trucks would be necessary to show corresponding effects in a substantial manner. First insights into the financial impact behind a 50% task relief for trailing have already been provided within the framework of this thesis.

Of course, our elaborations on the combinatorial problem of routing, scheduling and platooning under consideration of strict European transport law may also be transferred to other legal environments like those in the USA, Canada or Australia, for example. Platooning as a state-of-the-art transport technology necessitates an adequate highway infrastructure – a requirement which these countries undoubtedly fulfill. Publications for initial insights into the respective regulations of these states, where driving in train-like convoys can well become a reality soon, are mentioned in subsection 3.4.1.

Moreover, the allowed number of trucks within a single platoon will probably be limited in the future. Hence, the impact of such a restriction on platoon formation and dissolution should get some research attention as well. Let us assume a limit of 3 trucks. What if a fourth truck could easily join the convoy and save fuel or even some costly break or rest period time, but without the necessary legal support? The overall financial benefits from platooning would most likely suffer under such a limitation as more trucks would have to take the leader’s position in a platoon or even travel individually. This also raises the question of fairness then. Policy makers need to have some information on that as well to make sound decisions regarding that issue. Adapted versions of the exact EU-TPP model, the SPH or the PRH could give insights into this direction as well.

After addressing the impact of important influence factors on platooning in a qualitative way, more quantitative experiments are required with regard to different wage levels, manning options, penalty cost rates and further fuel-related aspects. As we have seen, these could heavily influence the decision whether to form or join a platoon or not. Here, especially mixed conditions call for more attention.

But also country-specific tolls can have an influence on the benefits from truck platooning, especially when it comes to balance the additional cost for potential detours. Being responsible for the third largest share of a truck's TCO, the interrelation between platoon coordination and toll roads as alternative route segments for highways is definitely worth some focus.

Another very important aspect for future research is the inclusion mutual compensation mechanisms into our presented modeling approaches in order to evaluate their actual effects for platooning decisions. As these are expected to be of highest importance for the success of platooning, it is firstly necessary to evaluate their respective impact on platoon coordination and secondly to compare their performance for the identification of the most suitable cost sharing strategy. Next to fuel consumption, other factors like the truckers' respective driving time status must be taken into account to decide upon reasonable role allocations within a platoon.

Furthermore, we still assumed a constant speed level without impeding circumstances for the trucks in our thesis. But since the benefits of platooning as well as the exact timing of compulsory breaks, rest periods and waiting times are highly dependent on smooth traffic conditions, the consideration of travel time uncertainty represents another interesting area to be analyzed. Next to a stochastic component, generally different speed options could be incorporated into our EU-TPP-based models. Luo et al. (2018) already investigated the mere interrelation between multiple speed levels and platooning and thus serve as a good reference.

In all respects though, larger-scale experiments with a larger amount of nodes, edges and trucks in the network are desirable. Simplifying assumptions, like equal distances between the single locations to account for appropriate multiples of 15 min time steps, could be avoided by the possible implementation of auxiliary nodes after each single time interval, for example. In doing so, the level of detail is increased automatically and we would be able to get closer insights into large-scale applications of platooning based on real-world instances.

However, at the end of the day, computational complexity is and will still remain the major challenge for platoon coordination to become a mature daily process. We have shown that the inclusion of mandatory breaks and daily rest periods in the EU-TPP already increases the anyway large efforts to find (near)optimal solutions without their consideration. In order to be able to address any of the aforementioned research directions in-depth at all, practicable strategies must be in place which take computational efficiency to the next level. This will be one of the key requirements for the future. Concerning this matter, new sophisticated heuristic approaches – maybe partly based on already existing strategies from platooning-, driving time- or VRP-related literature – have to be developed. Additional efficiency gains could be achieved by smartly implemented pruning parameters or new auxiliary constraints similar to the one from subsection 4.4.1.

Other concepts like rolling horizon planning could represent another promising way to tackle the coordination of platoons. Being temporally disaggregated into several smaller submodels, the overall problem of platooning is generally easier to solve due to discretely determined time horizons which are taken into account. Moreover, it would also be possible to consider updated truck schedules or new potential convoy partners for platooning decisions as soon as their respective tours are announced. This paves the way for the integration of OTFP-based approaches where platoons are formed en route by slight speed profile adjustments as well.

While we have still focused on coordinating platoons by merely planning their formation in advance of a trip, politics has to decide upon the best method to bring the disruptive transport technology to the road. "Platooning will only become successful if the crucial stakeholders in the supply chain have a positive business case with regards to platooning" (Janssen et al., 2015). For this reason, the different strategies – be it SOS, OTFP or a combination of both within the framework of ORP – need to be compared and financially validated based on their respective benefits for fleet managers. Our exact EU-TPP model as well as the two derived matheuristics provide a sound basis to get further insights into this direction. Ultimately, there is no doubt that platooning will only display its entire potential when a synchronization of forward planning with detailed routing decisions, jointly coordinated schedules and speed adjustment maneuvers is accompanied by an orchestrating and neutral PSP.

Of course, it must not be forgotten that there are further challenges apart from those coordination-related ones addressed within this thesis which must be overcome before the concept of truck platooning can finally be exploited in real-world applications. Next to technical aspects relating to the vehicles' digital communication pattern with their surrounding environment, questions of adequate road infrastructure or liability in case of accidents still need to be addressed, among many other things, in order to calculate the entire economic business case.

All in all, designing and scheduling cost-efficient tours by means of intelligently coordinated convoys is and will still remain a challenging task. But the societal and economic benefits provided by truck platooning are remarkable in every way. Of course, there is still a lot of work that needs to be done to make it an everyday reality. However, one thing is sure: the Digital Age allows for rapid developments and considerable improvements in technology. And maybe soon, the cloud-based logistics platform RIO will not only be able to offer new digital services like freight ridesharing via LOADFOX – but also an integrated approach, allowing to exploit the promising new concept of truck platooning.

"Our customers, and with them the entire trans-

> portation industry, and, last but not least, the environment, will reap the benefits of connected digital transportation" (Volkswagen, 2017). – Markus Lipinksy, Chief Executive Officer of RIO

References

Adler, A., Miculescu, D., and Karaman, S. Optimal policies for platooning and ride sharing in autonomy-enabled transportation. In *Massachusetts Institute of Technology, Cambridge (Massachussetts)*, 2016.

Al Alam, A., Gattami, A., and Johansson, K. H. An experimental study on the fuel reduction potential of heavy duty vehicle platooning. In *13th International IEEE Conference on Intelligent Transportation Systems*, pages 306–311. IEEE, 2010.

Alam, A. *Fuel-efficient heavy-duty vehicle platooning*. PhD thesis, KTH Royal Institute of Technology, Stockholm (Sweden), 2014.

Alam, A., Besselink, B., Turri, V., Martensson, J., and Johansson, K. H. Heavy-duty vehicle platooning for sustainable freight transportation: A cooperative method to enhance safety and efficiency. *IEEE Control Systems Magazine*, 35(6):34–56, 2015.

Archetti, C. and Savelsbergh, M. The trip scheduling problem. *Transportation Science*, 43(4):417–431, 2009.

Audy, J.-F., D'Amours, S., and Rousseau, L.-M. Cost allocation in the establishment of a collaborative transportation agreement—an application in the furniture industry. *Journal of the Operational Research Society*, 62(6): 960–970, 2011.

Bernhardt, A., Melo, T., Bousonville, T., and Kopfer, H. Scheduling of driver activities with multiple soft time windows considering european regulations on rest periods and breaks. Technical report, Schriftenreihe Logistik der Fakultät für Wirtschaftswissenschaften der htw saar, 2016.

Bernhart, W. Automated Trucks - The next big disruptor in the automotive industry. *Roland Berger, Chicago (USA) / Munich (Germany)*, 2016.

Besselink, B., Turri, V., Van De Hoef, S. H., Liang, K.-Y., Alam, A., Mårtensson, J., and Johansson, K. H. Cyber–physical control of road freight transport. *Proceedings of the IEEE*, 104(5):1128–1141, 2016.

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

Bonnet, C. and Fritz, H. Fuel consumption reduction in a platoon: Experimental results with two electronically coupled trucks at close spacing. Technical report, SAE Technical Paper, 2000.

Cruijssen, F., Dullaert, W., and Fleuren, H. Horizontal cooperation in transport and logistics: a literature review. *Transportation Journal*, pages 22–39, 2007.

Cruijssen, F., Borm, P., Fleuren, H., and Hamers, H. Supplier-initiated outsourcing: A methodology to exploit synergy in transportation. *European Journal of Operational Research*, 207(2):763–774, 2010.

Dahlberg, J., Engevall, S., Göthe-Lundgren, M., Jörnsten, K., and Rönnqvist, M. Incitements for transportation collaboration by cost allocation. *Central European Journal of Operations Research*, 27(4):1009–1032, 2019.

Davila, A., Aramburu, E., and Freixas, A. Making the best out of aerodynamics: Platoons. Technical report, SAE Technical Paper, 2013.

Deng, Q. and Ma, X. A fast algorithm for planning optimal platoon speeds on highway. *IFAC Proceedings Volumes*, 47(3):8073–8078, 2014.

D'Amours, S. and Rönnqvist, M. Issues in collaborative logistics. In *Energy, natural resources and environmental economics*, pages 395–409. Springer, 2010.

Eckhardt, J. European Truck Platooning Challenge 2016 - A fresh perspective on mobili-ty and logistics. Rijkswaterstaat, The Hague (Netherlands), 2015.

Eckhardt, J. European Truck Platooning Challenge 2016 - Creating next generation mo-bility: Lessons Learnt. Rijkswaterstaat, The Hague (Netherlands), 2016.

European Union. Directive 2002/15/ec of the european parliament and of the council of 11 march 2002 on the organisation of the working time of persons performing mobile road transport activities. *Official Journal of the European Union*, pages L–080, 2002.

European Union. Regulation (eu) no 165/2014 of the european parliament and of the coun-cil of 4 february 2014 on tachographs in road transport, repealing council regulation (eec) no 3821/85 on recording equipment in road transport and amending regulation (ec) no 561/2006 of the european parliament and of the council on the harmonisation of certain social legislation relating to road transport. *Official Journal of the European Union*, pages L60, 1–33, 2006.

European Union. Regulation (ec) no. 561/2006 of the european parliament and of the council of 15 march 2006 on the harmonisation of certain social legislation relating to road transport and amending council regulations (eec) no. 3821/85 and (ec) no. 2135/98 and repealing council regulation (eec) no. 3820/85. *Official Journal of the European Union*, pages L–102, 2014.

Frisk, M., Göthe-Lundgren, M., Jörnsten, K., and Rönnqvist, M. Cost allocation in collaborative forest transportation. *European Journal of Operational Research*, 205(2):448–458, 2010.

Goel, A. Vehicle scheduling and routing with drivers' working hours. *Transportation Science*, 43(1):17–26, 2009.

Goel, A. Truck driver scheduling in the european union. *Transportation Science*, 44(4):429–441, 2010.

Goel, A. The minimum duration truck driver scheduling problem. *EURO Journal on Transportation and Logistics*, 1(4):285–306, 2012a.

Goel, A. A mixed integer programming formulation and effective cuts for minimising schedule durations of australian truck drivers. *Journal of Scheduling*, 15(6):733–741, 2012b.

Goel, A. The canadian minimum duration truck driver scheduling problem. *Computers & Operations Research*, 39(10):2359–2367, 2012c.

Goel, A. and Gruhn, V. Drivers' working hours in vehicle routing and scheduling. In *2006 IEEE Intelligent Transportation Systems Conference*, pages 1280–1285. IEEE, 2006.

Goel, A. and Kok, L. Truck driver scheduling in the united states. *Transportation Science*, 46(3):317–326, 2012a.

Goel, A. and Kok, L. Efficient scheduling of team truck drivers in the European Union. *Flexible Services and Manufacturing Journal*, 24(1):81–96, 2012b.

Goel, A. and Rousseau, L.-M. Truck driver scheduling in canada. *Journal of Scheduling*, 15(6):783–799, 2012.

Goel, A. and Vidal, T. Hours of service regulations in road freight transport: An optimization-based international assessment. *Transportation Science*, 48(3):391–412, 2013.

Guajardo, M. and Rönnqvist, M. A review on cost allocation methods in collaborative transportation. *International Transactions in Operational Research*, 23(3):371–392, 2016.

Janssen, R., Zwijnenberg, H., Blankers, I., and de Kruijff, J. Truck platooning: Driving the future of transportation. *Driving The Future of Transportation, TNO Mobility and Logistics, Delft (Netherlands)*, 2015.

Kok, A. L., Meyer, C. M., Kopfer, H., and Schutten, J. M. J. A dynamic programming heuristic for the vehicle routing problem with time windows and european community social legislation. *Transportation Science*, 44 (4):442–454, 2010.

Kok, A. L., Hans, E. W., and Schutten, J. M. J. Optimizing departure times in vehicle routes. *European Journal of Operational Research*, 210(3):579–587, 2011.

Kopfer, H. W. and Buscher, U. A comparison of the productivity of single manning and multi manning for road transportation tasks. In *Logistics Management*, pages 277–287. Springer, 2015.

Kopfer, H. and Meyer, C. M. Ein Optimierungsmodell für die wöchentliche Tourenplanung unter Einbeziehung der EU-Sozialvorschriften. *Zeitschrift für Betriebswirtschaft*, 80(7-8):755–775, 2010.

Krajewska, M. A., Kopfer, H., Laporte, G., Ropke, S., and Zaccour, G. Horizontal cooperation among freight carriers: request allocation and profit sharing. *Journal of the Operational Research Society*, 59(11):1483–1491, 2008.

Labadie, N., Prins, C., Prodhon, C., Monmarché, N., and Siarry, P. *Metaheuristics for Vehicle Routing Problems*. John Wiley & Sons, Hoboken (USA), 2016.

Lammert, M. P., Duran, A., Diez, J., Burton, K., and Nicholson, A. Effect of platooning on fuel consumption of class 8 vehicles over a range of speeds, following distances, and mass. *SAE International Journal of Commercial Vehicles*, 7(2014-01-2438):626–639, 2014.

Larson, J., Kammer, C., Liang, K.-Y., and Johansson, K. H. Coordinated route optimization for heavy-duty vehicle platoons. In *16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013)*, pages 1196–1202. IEEE, 2013.

Larson, J., Liang, K.-Y., and Johansson, K. H. A distributed framework for coordinated heavy-duty vehicle platooning. *IEEE Transactions on Intelligent Transportation Systems*, 16(1):419–429, 2015.

Larson, J., Munson, T., and Sokolov, V. Coordinated platoon routing in a metropolitan network. In *2016 Proceedings of the Seventh SIAM Workshop on Combinatorial Scientific Computing*, pages 73–82. SIAM, 2016.

Larsson, E., Sennton, G., and Larson, J. The vehicle platooning problem:

Computational complexity and heuristics. *Transportation Research Part C: Emerging Technologies*, 60:258–277, 2015.

Liang, K.-Y., Mårtensson, J., and Johansson, K. H. When is it fuel efficient for a heavy duty vehicle to catch up with a platoon? *IFAC Proceedings Volumes*, 46(21):738–743, 2013.

Liang, K.-Y., Mårtensson, J., and Johansson, K. H. Fuel-saving potentials of platooning evaluated through sparse heavy-duty vehicle position data. In *2014 IEEE Intelligent Vehicles Symposium Proceedings*, pages 1061–1068. IEEE, 2014.

Liang, K.-Y., Mårtensson, J., and Johansson, K. H. Heavy-duty vehicle platoon formation for fuel efficiency. *IEEE Transactions on Intelligent Transportation Systems*, 17(4):1051–1061, 2016a.

Liang, K.-Y., van de Hoef, S., Terelius, H., Turri, V., Besselink, B., Mårtensson, J., and Johansson, K. H. Networked control challenges in collaborative road freight transport. *European Journal of Control*, 30:2–14, 2016b.

Lindberg, J. Blockchain technology in scania services: An investigative study of how blockchain technology can be utilized by scania, 2017.

Liu, P., Wu, Y., and Xu, N. Allocating collaborative profit in less-than-truckload carrier alliance. *Journal of Service science and Management*, 3(01):143, 2010.

LOADFOX. Ridesharing for road freight - The next evolution of freight exchange platforms, 2017. URL https://loadfox.eu/en/loadfox-en/. 12/31/2017.

Lozano, S., Moreno, P., Adenso-Díaz, B., and Algaba, E. Cooperative game theory approach to allocating benefits of horizontal cooperation. *European Journal of Operational Research*, 229(2):444–452, 2013.

Luo, F., Larson, J., and Munson, T. Coordinated platooning with multiple speeds. *Transportation Research Part C: Emerging Technologies*, 90:213–225, 2018.

Meisen, P., Seidl, T., and Henning, K. A data-mining technique for the planning and organization of truck platoons. In *Proceedings of the International Conference on Heavy Vehicles*, pages 19–22, 2008.

Meyer, C. M. Distributed decision making in combined vehicle routing and break scheduling. In *Vehicle Routing under Consideration of Driving and Working Hours*, pages 67–101. Springer, 2011.

Meyer, C. M. and Kopfer, H. Restrictions for the operational transportation planning by regulations on drivers' working hours. In *Intelligent Decision Support*, pages 177–186. Springer, 2008.

Minner, S. An optimal network flow formulation for Platooning. Chair for Logistics and Supply Chain Management, Technical University of Munich, Munich (Germany), 2017a.

Minner, S. Modeling work time regulations in the traveling salesman problem. Chair for Logistics and Supply Chain Management, Technical University of Munich, Munich (Germany), 2017b.

Nourmohammadzadeh, A. and Hartmann, S. The fuel-efficient platooning of heavy duty vehicles by mathematical programming and genetic algorithm. In *International Conference on Theory and Practice of Natural Computing*, pages 46–57. Springer, 2016.

Özener, O. Ö. and Ergun, Ö. Allocating costs in a collaborative transportation procurement network. *Transportation Science*, 42(2):146–165, 2008.

Prescott-Gagnon, E., Desaulniers, G., Drexl, M., and Rousseau, L.-M. European driver rules in vehicle routing with time windows. *Transportation Science*, 44(4):455–473, 2010.

RIO. Get to know RIO - A platform for the entire logistics industry, 2017. URL https://rio.cloud/en/get-to-know-rio.html. (12/31/2017).

Saeednia, M. and Menendez, M. Analysis of strategies for truck platooning: Hybrid strategy. *Transportation Research Record*, 2547(1):41–48, 2016.

Schmeidler, D. The nucleolus of a characteristic function game. *SIAM Journal on applied mathematics*, 17(6):1163–1170, 1969.

Shapely, L. A value for n-person games. contributions to the theory of games, 1953.

Shoubi, M. V., Barough, A. S., and Amirsoleimani, O. Application of cost allocation concepts of game theory approach for cost sharing process. *Research Journal of Applied Sciences, Engineering and Technology*, 5(12): 3457–3464, 2013.

Sokolov, V., Larson, J., Munson, T., Auld, J., and Karbowski, D. Platoon formation maximization through centralized routing and departure time coordination. *arXiv preprint arXiv:1701.01391*, 2017.

Stiglic, M., Agatz, N., Savelsbergh, M., and Gradisar, M. The benefits of meeting points in ride-sharing systems. *Transportation Research Part B: Methodological*, 82:36–53, 2015.

Tavasszy, L. A. The value case for truck platooning. Delft University of Technology, Delft (Netherlands), 2016.

Tijs, S. H. and Driessen, T. S. Game theory and cost allocation problems. *Management Science*, 32(8):1015–1028, 1986.

Transport-Online. Wirtschaft + Politik - Platooning: Bund fördert vernetzte Lkw Kolonnen, 2017. URL https://www.transport-online.de/Transport-News/Wirtschaft-Politik/17148/Platooning-Bund-foerdert-vernetzte-Lkw-Kolonnen. 12/31/2017.

Tsugawa, S. An overview on an automated truck platoon within the energy its project. *IFAC Proceedings Volumes*, 46(21):41–46, 2013.

Van De Hoef, S., Johansson, K. H., and Dimarogonas, D. V. Fuel-optimal centralized coordination of truck platooning based on shortest paths. In *2015 American Control Conference (ACC)*, pages 3740–3745. IEEE, 2015a.

Van De Hoef, S., Johansson, K. H., and Dimarogonas, D. V. Coordinating truck platooning by clustering pairwise fuel-optimal plans. In *2015 IEEE 18th international conference on intelligent transportation systems*, pages 408–415. IEEE, 2015b.

van de Hoef, S., Johansson, K. H., and Dimarogonas, D. V. Computing feasible vehicle platooning opportunities for transport assignments. *IFAC-papersonline*, 49(3):43–48, 2016.

van de Hoef, S., Johansson, K. H., and Dimarogonas, D. V. Efficient dynamic programming solution to a platoon coordination merge problem with stochastic travel times. *IFAC-PapersOnLine*, 50(1):4228–4233, 2017.

Vanovermeire, C. and Sörensen, K. Measuring and rewarding flexibility in collaborative distribution, including two-partner coalitions. *European Journal of Operational Research*, 239(1):157–165, 2014.

Vanovermeire, C., Sörensen, K., Van Breedam, A., Vannieuwenhuyse, B., and Verstrepen, S. Horizontal logistics collaboration: decreasing costs through flexibility and an adequate cost allocation strategy. *International Journal of Logistics Research and Applications*, 17(4):339–355, 2014.

Verheyen, W. Legal infrastructure for cooperation as a catalyst for platooning. *Proceedings of the BIVEC-GIBET transport Research days 2017, Towards an autonomous and interconnected transport futuure*, pages 103–110, 2017.

Volkswagen. Volkswagen Truck & Bus - making logistics ready for the future, 2017. URL https://www.volkswagenag.com/en/news/2017/10/VW_Truck_and_Bus_Logistik.html#. 12/31/2017.

Wittenbrink, P. *Transportkostenmanagement im Straßengüterverkehr: Grundlagen-Optimierungspotenziale-Green Logistics*. Gabler, Wiesbaden (Germany), 2011.

Xu, H., Chen, Z.-L., Rajagopal, S., and Arunapuram, S. Solving a practical pickup and delivery problem. *Transportation science*, 37(3):347–364, 2003.

Zhang, W., Ma, X., and Jenelius, E. Planning of heavy-duty vehicle platoon formulation: basic scheduling problem considering travel time variance. In *Transportation Research Board 95th Annual Meeting*, 2016.

Zhang, W., Jenelius, E., and Ma, X. Freight transport platoon coordination and departure time scheduling under travel time uncertainty. *Transportation Research Part E: Logistics and Transportation Review*, 98:1–23, 2017.