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Szymon Albiński
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Stefan Minner

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Bureau de Montréal
Université de Montréal
C.P. 6128, succ. Centre-Ville
Montréal (Québec) H3C 3J7
Tél. : 1-514-343-7575
Télécopie : 1-514-343-7121

Bureau de Québec
Université Laval,
2325, rue de la Terrasse
Pavillon Palasis-Prince, local 2415
Québec (Québec) G1V 0A6
Tél. : 1-418-656-2073
Télécopie : 1-418-656-2624

The Day-before Truck Platooning Planning Problem and the Value of Autonomous Driving

Szymon Albiński[1,*], Teodor Gabriel Crainic[2], Stefan Minner[1]

1. Technical University of Munich, School of Management, Arcisstrasse 21, D-80333 Munich, Germany / www.log.wi.tum.de
2. Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT) and Department of Management and Technology, Université du Québec à Montréal, P.O. Box 8888, Station Centre-Ville, Montréal, Canada H3C 3P8

Abstract. Truck platooning promises not only fuel savings, but is also a bridging technology for the development towards autonomous trucking. It is presumed that this transition phase will happen in three steps, where in the first two steps the trucks need to be manned. Consequently, the routing and scheduling of trucks under the platooning option will be affected by driving time regulations. In this paper, we study the central planning of platoons and truck routes through a multi-brand platform, where we consider the day-before planning problem for routing and scheduling the trucks as an important part of the coordination process. We introduce a novel mixed-integer linear programming formulation that is defined on a time-expanded two-layer network. Thereby, we assume limits to the maximal platoon size and fixed time-windows and include regulations on mandatory rest periods and breaks. Moreover, we anticipate a higher degree of autonomous driving by including a rest-while-trailing option. That is, the driving times of those drivers who are trailing with their trucks in a platoon are only partially counted, or not at all. We develop a pre-processing procedure that allows us to significantly reduce the problem size of the input that we provide to a linear solver. The results of a computational study demonstrate the efficiency of our solution approach. By analyzing the impact of driving time regulations, the effects of different network structures, varying fuel savings parameters as well as changing buffer times, we provide insights into the optimal planning and management of truck platoons through a central platform. Assessing the value of platooning and the value of automation, we show that truck platooning is beneficial in all three stages of automation.

Keywords. Cooperative transportation, time-space network, truck platooning, autonomous trucking, green logistics.

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* Corresponding author: szymon.albinski@tum.de

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1. Introduction

Truck platooning is a form of shared transportation, where several trucks drive in close succession in order to reduce their air resistance in the predecessor's slipstream and thus their fuel consumption. Being digitally connected and using autonomous driving technology, the platoon followers automatically steer, break and accelerate with the first truck, the platoon leader. Thus, the trucks in this train-like formation can travel with smaller safety distance, which can help with reducing fuel consumption and thus CO_2 emissions. For example, in a platoon of size three, this allows for fuel savings up to 16% for the followers and even the leader can save up to 7.5%, due to less vortexes behind the truck (Tsugawa, Kato, and Aoki 2011).

A reduced fuel consumption translates directly into less air pollution. Between 1990 and 2016, transport greenhouse gas emissions in the European Union increased by 18% to 931 million tonnes of CO_2 equivalent (European Commission 2018). This represents 21% of all European greenhouse gas emissions, making the transport sector the second largest producer of greenhouse gases. In addition, this is the only sector whose greenhouse gas emissions have risen beyond the value of 1990. In 2011, the EU Commission decided to reduce Europe-wide greenhouse gas emissions by 80% by 2050 (European Commission 2011). The transport by road carries the main burden of freight transport in Europe with a share of 75% (European Union 2017). Consequently, the European Union identified road freight transportation as one of the pillars of its concepts towards achieving the GHG goals. In February 2019, the European Parliament and the European Commission agreed on a bill that obligates truck manufacturers to reduce the average CO_2 emissions of newly built trucks by 15% until 2025 and 30% by 2030, compared to the status in 2019 (Reuters 2019). Similar emission limits have already been established in the United States and Canada. Since current Diesel engines already work highly efficient, truck manufactures have to develop and combine new technologies to meet such directives (Reuters 2019). Obviously, the introduction of hybrid or electric trucks will play a crucial role. Nevertheless, combining several trucks into *truck platoons* offers a further promising approach for saving energy (Diesel or electricity) and thus reducing GHG emissions and meeting the goals.

Besides a reduced fuel consumption and less CO_2 emissions, truck platooning bears the potential to increase space utilization and thus improve the traffic flow on highways (Van Arem, Van Driel, and Visser 2006). Furthermore, platooning can help towards improving road safety (TNO Mobility and Logistics 2015). Therefore, companies are continuing their efforts on realizing this form of collaborative trucking. In July 2019, Peloton Technology (2019) announced the release of a new platooning technology that allows the platoon followers to be driver-less. This so-called "Level 4 automation" can help to reduce the room for human errors like inattention, distraction or fatigue (Truck News 2019). In 2007, 85% of all road accidents were a result of human errors and 21% of all truck accidents happened while driving in a convoy (International Road Transport Union and European Commission 2016).

However, in many regions of the globe, the trucking industry is fragmented, which may make platooning somewhat difficult to implement. For example, in Canada, the market of road freight transportation is highly segmented with 66,751 companies operating in December 2016 (Government of Canada 2016). A similar situation exists in Europe: 550,000 companies offer trucking transportation and more than 80% of the companies employ less than the EU average of 5.2 people per company (European Commission 2017). Consequently, in both regions, a platform that centrally coordinates the movement and formation of platoons would lead to the highest cost savings.

Moreover, platooning can be used as a bridging technology towards fully autonomously driving trucks. In 2018, the European Automobile Manufacturers' Association (2018) (*ACEA*) published an "EU Roadmap for Truck Platooning" with the intention to introduce a *multi-brand platooning platform* that centrally coordinates individually driving trucks into platoons in the European Union by 2023. Besides, the ACEA assumed that drivers are only required as long as trucks cannot drive fully autonomously. Already allowing the truck drivers of the trailing trucks to (partially) rest would increase the time of trucks on the road. This would help to address the problems of overfilled parking lots along highways (Deutsche Welle 2018) and the shortage of truck drivers (International Road Transport Union 2018). According to the ACEA roadmap, the transition phase will happen in three stages, which we call in the following *ACEA stages*, or simply *stages*:

- *Stage 1*: All drivers need to be attentive while driving in a platoon.
- *Stage 2*: The drivers of the trailing trucks can (partially) rest while driving in a platoon.
- *Stage 3*: Trucks are driving fully autonomously, no drivers are needed or all drivers rest.

Since trucks typically cover long distances, the formation of platoons in Stages 1 and 2 will be affected by driving time regulations that apply in many countries. In the European Union, the EU social legislation *Regulation (EC) No 561/2006* (European Union 2006) on driving times, breaks and rest periods, as well as *Directive 2002/15/EC* (European Union 2002), define the framework for the truckers' working times. Similar legislation can also be found in many other countries, for instance in Canada (*Commercial Vehicle Drivers Hours of Service Regulations*) or in the United States (*Hours of Service Regulations*), and several authors have shown that, even for individual trucks, such regulations make the computation of cost-efficient tours a challenging task (Goel and Vidal 2013).

Both points, a multi-brand platform and driving time regulations in the context of truck platooning, have been only partially discussed in the academic literature. Van de Hoef, Johansson, and Dimarogonas (2018) describe the process of a central *platoon coordinator* that determines such routes for carriers that their trucks arrive at their destination within the desired time-window while simultaneously exploiting fuel savings through platooning. However, no platform-based planning methodology has been proposed in the literature so far. Since the platform takes over the routing and scheduling of the trucks, it has to return the information to the carriers with a certain lead time such that the carriers can instruct their truck drivers in time. We assume that this lead time is one day. Consequently, we have to formulate and solve the day-before planning problem.

According to the consulting firm Strategy& (2018), Stage 2 will be reached in 2025 and Stage 3 in 2030. The ACEA expects that truck platooning in Stage 1 will be fully possible across Europe by 2023, after the roll-out to start in 2020. Thus, driving time regulations will be a key factor in the successful implementation of truck platooning. Yet, the only work that relates driving time regulations to platooning is the one by Larsen, Rich, and Rasmussen (2019), the authors considering solely Stage 2, where the driver of a trailing truck can skip a break since he is resting-while-trailing. This is formulated under strict assumptions such as that the trucks drive on fixed routes and platoons can only be formed at a single hub node.

We conclude that there is a lack of methodology that allows a platform to perform the day-before planning of the routes and schedules under driving time regulations with a large number of trucks and to return this information in time to the carriers. In this paper, we aim to close this research gap by discussing the idea of a platform-based business model for multi-brand platooning and by proposing a model for the day-before planning problem for all three ACEA stages. Our contribution is three-fold:

1. We propose a new mathematical model for the day-before planning of truck platoons under platoon-size limits, hard time windows and driving time regulations. This can be used in all three ACEA stages.
2. We develop a pre-processing procedure that allows us to solve large instances of this $\mathbb{NP}-$hard problem with off-the-shelf solvers in reasonable size. Consequently, our model is ready to use in industry without further implementation effort.
3. For all three stages of automation, we provide insights into the optimal planning of platoons under varying parameters and different network structures. Furthermore, we discuss the value of platooning and the value of autonomous driving.

The remainder of this paper is structured as follows. In Section 2, we describe the current legislation on working hours for truck drivers in the European Union, Canada and the United States and summarize the literature. In Section 3, we describe the problem and basic assumptions. The model is introduced and explained in Section 4. In Section 5, we propose a pre-processing procedure that reduces the input size. In Section 6, we describe the computational study and present the results for all three ACEA stages. Section 7 concludes the paper.

2. Literature review

In this section, we give first an overview on the current legislation on driving times in the European Union, Canada and the United States. Then, we review the literature on the trip planning under driving time regulations and on the planning of truck platoons.

2.1. Legal framework for truck driver scheduling in different countries

The driving and working times of truck drivers in the European Union are regulated by *Regulation (EC) No 561/2006* and *Directive 2002/15/EC*. While the former defines the maximum driving times along with minimum breaks and rest periods for different time horizons (European Union 2006), the latter legislation formulates the general working conditions for truck drivers (European Union 2002).

According to *Regulation (EC) No 561/2006*, a break of at least 45 min has to be taken after a maximum driving period of 4.5 h. As soon as the maximum daily driving time of 9 h is reached, the driver needs to take a rest period for at least 11 h. Furthermore, a rest period has to be completed within 24 h after the end of the last rest period. In the course of one week, a driver must not drive more than 56 h, while the limit for the total number of driving hours in two weeks is 90 h. Between two weeks of working, a driver has to rest at least 45 h. To give the fleet operators more flexibility, the legislator introduced so-called *splitting rules*. According to these rules, a break can be divided into two parts, where the first one has to be at least 15 min and the second 30 min. Similarly, a daily rest can be divided into two parts with a minimum of 3 h for the first part and 9 h for the second part. This means that drivers are granted an additional hour if they split up a daily rest period. In addition to these *splitting rules*, driving times can be extended and rest periods can be reduced under certain conditions. However, such extensions have to be compensated afterwards by additional rest periods and thus should only be used in unforeseeable events. While *Regulation (EC) No 561/2006* sets a European framework for driving times, *Directive 2002/15/EC* extends the temporal rules to restrict night work and working times on and off the vehicle (Goel 2018). Off-vehicle duties are not related to driving and comprise tasks like administration, freight handling, maintenance or waiting times at customer sites. Consequently, they get more relevant if we wish to optimize delivery tours like Vehicle Routing Problems with Time Windows. Thus, we consider only *Regulation (EC) No 561/2006*, which mainly influences long-distance tours.

Similar to the European Union, other countries have established comparable rules. In Canada, the *Commercial Vehicle Drivers Hours of Service Regulations* (Government of Canada 2005) grant the carriers more flexibility: they require that a driver has to take a daily rest of 8 h after having driven for 13 h. In addition, a total of 2 h of breaks (called *off-duty time*) has to be taken during these 13 h with each break lasting at least 30 min. Furthermore, a rest period has to be started within 16 h after the end of the last rest period. Similar to the European rules, the splitting of breaks and rest periods is allowed. In territories north of Latitude 60° North, the driving times are extended to 15 h and a rest period has to be started 20 h after the last was finished.

In the United States, the *Hours of Service Regulations* (*HOS*) define the legal framework for truck drivers. Among other things, these regulations require that after 11 h of driving, a 10 h rest has to be taken. In addition, the *on-duty hours* are limited to 14 h (Goel and Kok 2012). This allows the drivers to do non-driving tasks, including meal and rest breaks.

2.2. Trip planning for trucks under driving time regulations

Motivated by the introduction of *Regulation (EC) No 561/2006*, Goel (2009) studied the Vehicle Routing Problem with Time Windows (VRPTW) under those EU restrictions that affect the working times between two weekly rest periods. The study shows that pauses scheduled before the maximum driving time limit can help to meet narrow time windows at subsequent customers. Kok et al. (2010) extend this research direction by including all the regulations named in *Regulation (EC) No 561/2006* plus working time restrictions defined in *Directive 2002/15/EC*. Their computational results show that *Directive 2002/15/EC* has a high impact on the VRPTW solutions. Goel (2010) studies an open TSP for a weekly schedule under *Regulation (EC) No 561/2006*, which also allows splitting break and rest times into two parts. A key insight from the computational study is that the splitting of breaks increases the solution time of the heuristic, whereas split breaks do not lead to significantly better schedules.

Rancourt, Cordeau, and Laporte (2013) study long-haul trips under the United States Hours of Service (HOS) regulations. They formulate this problem as a Vehicle Routing Problem with multiple time-windows and develop a tabu search heuristic. From the computational study they conclude that the splitting of breaks can lead to better working schedules. Xu et al. (2003) study the impact of HOS on the transportation problem where a driver has to visit a certain sequence of locations. Studying a similar problem with single time windows, Archetti and Savelsbergh (2009) develop a polynomial runtime algorithm (cubic in the input size) to create schedules that are feasible with regard to the HOS regulations. Goel and Kok (2012) introduce an algorithm that creates a feasible schedule with a runtime that is quadratic in the input size. Goel and Rousseau (2012) show that the Canadian Commercial Vehicle Drivers Hours of Service Regulations are more permissive than the HOS.

2.3. Routing and scheduling of truck platoons

Larsson, Sennton, and Larson (2015) were the first to introduce a mixed-integer linear programming formulation for the problem of routing trucks under the option of platooning. The authors call it the Unlimited Platooning Problem (UPP) since, in this model, trucks have no latest arrival time and the platoon size is not restricted. As the UPP belongs to the class of $\mathbb{NP}$-hard problems, the authors propose two construction heuristics for the design of platoons: the Best Pair heuristic and the Hub heuristic. The former identifies the combination of trucks with the highest savings potential. In the latter, the trucks are partitioned into groups based on the edge-similarity of their corresponding shortest paths. Each group is then assigned to hub nodes and platoons can be built within these groups only.

In a follow-up, Larson, Munson, and Sokolov (2016) use different characteristics of the platooning problem to reduce the problem size. Among other things, they show that there exists a bound on the maximal detour length within which the fuel savings through platooning exceed the additional fuel expenses for every truck. They use this bound to set decision variables, which would lead to infeasible or sub-optimal solutions, to zero. This pre-processing allows a reduction of the number of possible paths for each truck while simultaneously solving the platooning problem. With this approach, they solve instances for up to 25 trucks in a 10×10 grid with unit distance to optimality. Moreover, the authors apply their method to the Chicago highway network with 100 trucks. Out of the 4,553 nodes in this network, the authors select five node pairs, each of them representing the origin and destination for 20 trucks. In most cases, the instances can be solved within a one percent optimality gap in between 100 and 300 seconds.

Van De Hoef, Johansson, and Dimarogonas (2015) allow for different speed profiles. In their heuristic, platoons are formed based on the shortest path and then a speed level is assigned to them. Following the idea of multiple speed levels, Luo, Larson, and Munson (2018) propose a mixed-integer linear problem that uses different speed profiles in order to improve the formation of platoons by means of waiting times. For bigger instances, the authors propose a cluster-first-route-second decomposition approach. Van de Hoef, Johansson, and Dimarogonas (2018) introduce the idea of a centralized platoon coordinator that determines routes in such way that the trucks arrive at their destination in time while fuel savings through platooning are also exploited. Due to the high complexity of the problem, the authors suggest a heuristic that schedules the trucks on fixed routes with the platoon size limited to two vehicles.

Zhang, Jenelius, and Ma (2017) consider uncertain travel times in the planning of truck platoons. They conclude that delays of a single truck can be propagated by the formation of platoons and thus make truck platoons unattractive. Boysen, Briskorn, and Schwerdfeger (2018) come to a similar conclusion that, due to tight schedules, delays will outweigh the benefits of fuel savings. However, the authors point out that if wages could be reduced, e.g. by driver-less platoon followers, platoons might become profitable even with penalties for delays. In their literature review, Bhoopalam, Agatz, and Zuidwijk (2017) mention the platoon formation under restrictions such as a limited platoon size could be an interesting future research direction. Scherr et al. (2018) show that, besides saving fuel, the technology of truck platooning can also be used to guide autonomously driving trucks through areas that require a truck driver. The authors describe a scenario in city logistics where autonomous trucks serve customer requests in certain districts. However, to get to and from the depot outside the city, the trucks are merged into a platoon where the leading truck is manned. The results of the controlled computational study indicate that this concept can render considerable cost savings.

Chardaire et al. (2005) use a time-space expanded network to solve the Convoy Movement Problem. The authors propose a Lagrangian relaxation to solve the problem. Their computational study shows that, with this approach, they can achieve small optimality gaps within half an hour for instances with 17 convoys. For freight trains, Zhu, Crainic, and Gendreau (2014) propose a mixed-integer linear model defined on a three-layer time-space network that allows them to track the movements of the trains, blocks and cars, including delays and waiting times.

Larsen, Rich, and Rasmussen (2019) take mandatory breaks into account and study the hypothetical case that the platoon followers' driving time can be counted as rest time and that, the drivers can skip breaks. The authors assume that all trucks travel on fixed routes that pass one single hub. At this hub, a platooning service provider coordinates the formation of platoons, forcing the trucks to wait if necessary. The results of their computational study with data from a European highway network show that rest options make trips profitable. Besides, the trucks' waiting times increase with the distance they drive.

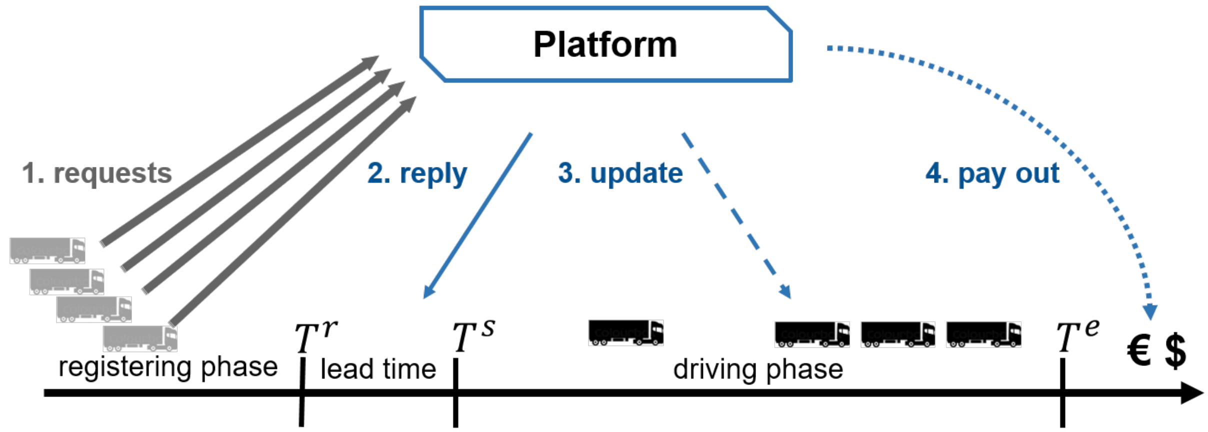
In sum, the literature lacks methodology to plan the formation and routing of platoons, particularly from a platform point of view. Moreover, driving time regulations and the maximal platoon size were not studied in this context.

3. Problem description and assumptions

Our goal is the coordination of individual truck trips into truck platoons through a central platform. Hereby, we assume that all carriers are willing to cooperate due to the prospect of reduced trucking cost. We propose the coordination process of a multi-brand platform (or simply *platform*) as follows:

1. Carriers register their trips for a certain time period $\mathcal{T} = [\mathcal{T}^s; \mathcal{T}^e]$ (e.g. one week) until the registration deadline $\mathcal{T}^r < \mathcal{T}^s$, which is one day ahead. Thereby, they provide information about the origin and destination as well as earliest possible start and latest possible arrival times. To achieve the highest potential savings through truck platooning, trucks may deviate from the shortest route in order to travel together with other trucks. Therefore, all carriers who enter their trips agree to the terms that their trucks may deviate from the shortest paths as long as the time windows are met and the traveling costs are not higher than what would be if every truck drove by itself.

Figure 1 **Visualization of the coordination process with the platform.**



2. After $\mathcal{T}^r$, the platform informs the carriers if the trips can be integrated in a platoon and by how much the travel cost can be reduced.
3. The trucks realize the trips according to the routes and schedules provided by the platform. These may change due to delays or no-shows of trucks.
4. As soon as all trips are finished, the promised savings are payed to the carriers, with the platoon leaders being compensated for their higher costs.

Figure 1 illustrates the time line of that process. In order to give the carriers an acceptance note and to grant some lead time, the platform has to reply in step two before the planned period starts. This can be done by solving a *day-before planning problem*. The objective is to reduce the total cost of all registered trucks through platooning. Naturally, this can lead to sub-optimal solutions for the individual trucks. However, these additional expenses are compensated through the distribution of the savings among all platoon members. Due to the limit on the platoon size, it might happen that several platoons are traveling simultaneously in the same time step. In that case, the cost savings are evenly distributed among all trucks traveling in one of those platoons. Otherwise, trucks in the smaller platoon would be discriminated as far as their costs are concerned. Other redistribution schemes, partially based on Game Theory, can be found in Bhoopalam, Agatz, and Zuidwijk (2017).

We assume that platoons are only formed on roads that provide a highly isolated environment. This is motivated by the observation that it is easier to implement the technology of autonomously driving trucks in such environments. Highways meet these requirements, which is why we focus on this type of road while acknowledging that there are also other types of roads where platoons can be formed (e.g. federal highways in Germany or roads in Canada's Northwest Territories). We assume that all trucks are traveling at the same, constant speed. Consequently, we say that a platoon formation or disbanding can only happen at parking lots that are on highways. Usually, the origins and destinations of the trucks are located away from the highways. Thus, we assume that the trucks have to drive on the first and last miles individually.

Similarly to Goel (2009, 2010), we focus on those parts of *Regulation (EC) No 561/2006* that affect the driving time between two weekly rest periods. This is motivated by the consideration that our planning horizon for the platoons is at most one week. Since the aim of this paper is to provide a general proof of concept of the model and to evaluate the impact of driving time regulations, the splitting rules are dropped. However, it is a straightforward task to incorporate these rules into the basic model and this extension will be left for future work.

4. The Restricted Truck Platooning Problem

In this section, we model the day-before planning as a mixed-integer linear program. We call this problem the *Restricted Truck Platooning Planning Problem* (*RTP*), which can be formulated in the respective ACEA stages as follows:

- *RTP-1*: All drivers need to be attentive and follow the driving time regulations. Platooning allows to save fuel cost.
- *RTP-2*: Only the leading truck driver's time is fully counted. The drivers of the trailing trucks can perform other tasks or (partially) rest. Platooning allows to save personnel cost and fuel cost.
- *RTP-3*: The trucks are unmanned. Thus, there are no personnel costs and no driving time regulations need to be considered. Platooning allows to save fuel cost.

We introduce the basic notation in Section 4.1 and present the two-layer time-space expanded network in Section 4.2. The mixed-integer linear formulation of RTP-3 is introduced in Section 4.3. In Section 4.4, we extend the formulation to RTP-1 and RTP-2 by showing how the basic European driving time regulations, the Canadian Commercial Vehicle Drivers Hours of Service regulations and the U.S. Hours of Service regulations can be modeled. In Section 4.5, we present valid inequalities that help to tighten the formulation.

4.1. Basic notation

We introduce a node set $\mathcal{V}$ that includes (i) the origins and destinations of the trucks, (ii) the parking lots along the highways and (iii) intersection nodes that represent the highway entrances and exits. We call the last two types of nodes *waypoints* and collect them in the subset $\mathcal{V}^W \subsetneq \mathcal{V}$. The set $\mathcal{A}$ contains all (physically) feasible connections between the nodes. We introduce superscripts o and d to indicate the origin or destination of an arc $a \in A$. That is, we write $a = (a^o, a^d)$. We call $\mathcal{G} := (\mathcal{V}, \mathcal{A})$ the *supporting network*. τ_{ij} denotes the travel time between nodes i and j.

Since every trip is associated with a truck, we refer to trucks and denote the set of all trucks by $\mathcal{K}$. Every truck has an earliest starting time e_k at its origin o_k and a latest arrival time l_k at its destination d_k. If a truck is doing several trips, it is represented by several trucks in the model. The departure and arrival times have then to be adapted accordingly. When trailing in a platoon, the fuel consumption is reduced by $\eta^f \in [0,1]$ for the followers and by $\eta^l \in [0,1]$ for the leader. $\rho \in [0,1]$ defines the share of the driving time that is not counted in the rest-while-trailing option. That is, if $\rho = 1$, the driving time of the drivers in the following trucks is not credited at all. The size of a platoon is limited by ς and the set $S := \{2,\dots,\varsigma\}$ comprises all size options. Since the travel times might depend on the time-period $t \in T$, t_{ij} denotes the travel time between $i,j \in \mathcal{V}$ at time-step $t \in T$.

We assume that all truck drivers start their tours completely rested and that breaks, rest periods and additional waiting times can only be taken at the waypoints. Furthermore, truck drivers are assigned to the same truck throughout the whole planning period. Consequently, the driving times of a driver correspond to those of a truck. After driving for a period with a length of at most D^b (4.5 h), a minimum break time B (45 min) has to be taken. After a total driving time of 9 h (D^r), every driver has to rest a minimum time of 11 h (R). Furthermore, after having finished the last rest period, the driver has to complete the next rest period inside a 24-hour-window (D).

c^f_{ak} describes the fuel cost of truck k when it travels on arc a, whereas c^l_{ak} describes the wages that have to be paid on this arc. For voluntarily waiting, wages still have to be paid. Therefore, we impose cost c^w on waiting arcs. They correspond to the wages that have to be paid for one time step. When drivers take a mandatory break or rest, or when they rest-while-trailing, we assume that no wages are paid. Since trucks have to stop on a parking lot to form or leave a platoon, we say that joining or leaving a platoon costs c^p. This cost is independent of the truck or location.

Our objective is to minimize the total travel cost of all trucks through platooning. That is, we assume that the overall savings are fairly distributed such that no truck in the platoon is worse off, i.e. any allocation belonging to the core could be a feasible distribution of savings.

4.2. Time expanded two-layer network

To synchronize the schedules of the trucks, we divide the planning period $\mathcal{T}$ into h time steps of equal length. The resulting set of time periods is denoted by T and we obtain a time-space network where each node $v \in \mathcal{V}$ is expanded h times. Let i be a node of this time-space network. Then, the functions $f : V \to \mathcal{V}$ and $g : V \to T$ determine the node and the time step, which is represented by i. That is, $f(i) = v$ and $g(i) = t$. The network consists of two layers: the truck layer and the platoon layer.

Truck layer: The node set V_K contains the time-expanded *truck nodes*, that is: $|V_K| = h \cdot |\mathcal{V}|$. $V_K^W \subsetneq V_K$ represents all waypoint nodes in the time-space network. We introduce A_K, the set of truck arcs. An arc $(i,j) \in A_K$ connects two nodes $i,j \in V_K$ when $g(j) - g(i) = \tau_{f(i),f(j)}$. To model the waiting option, we use *waiting arcs* that connect those nodes of the same waypoint node that differ in one time step, i.e. $i,j \in V_K^W$ with $f(i) = f(j)$ and $g(j) = g(i) + 1$. We call the resulting graph $G_K := (V_K, A_K)$ the *truck layer*.

Platoon layer: Platoons move within the *platoon layer* $G_P := (V_P, A_P)$. V_P represents the time-expanded nodes where platoons can be formed. They are the waypoint nodes and therefore the *platoon nodes* are a copy of V_K^W. Let $i \in V_K^W$ be a waypoint node in the time-expanded truck layer, then i_P denotes its copy in the platoon layer.

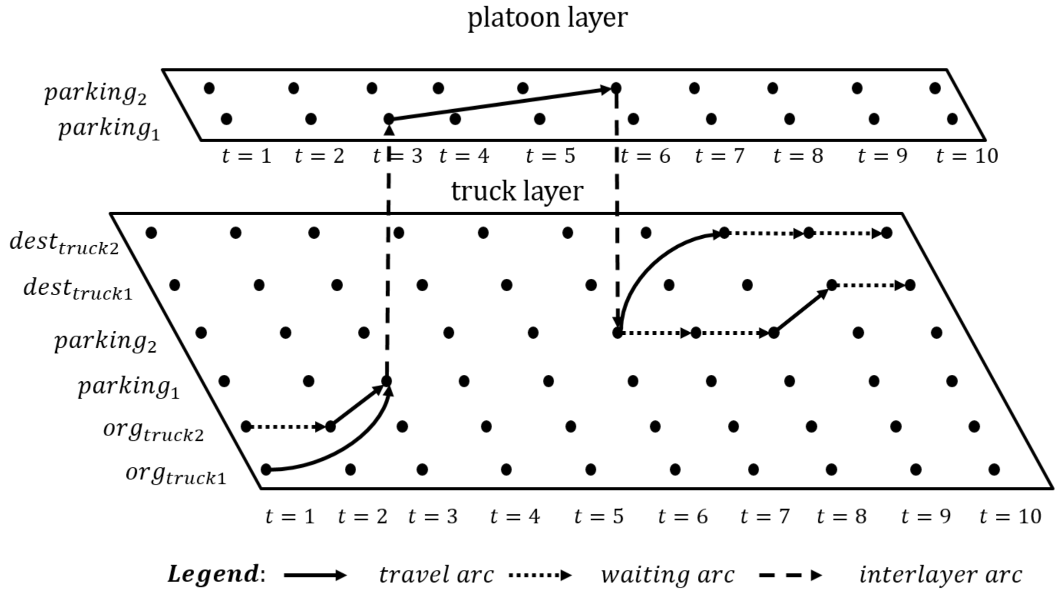
Two-layer network: To model the forming and disbanding of platoons, we introduce *interlayer arcs* $A_I = A_I^+ \cup A_I^-$. That is, A_I^+ contains all arcs (i, i_P), that represent the formation of a platoon at a waypoint node, whereas A_I^- comprise those arcs (j_P, j) that describe the disbanding of a platoon. The whole *layer network* $G := (V, A)$ is formed by the nodes $V := V_K \cup V_P$ and the arcs $A := A_K \cup A_P \cup A_I$.

Figure 2 shows an example of two trucks traveling in this two-layer time-space network. Truck 1 heads from its origin at step $t = 1$ to waypoint 1 in step $t = 3$ where, together with truck 2, it forms a platoon of size $s = 2$ that drives to waypoint 2 – where the platoon is disbanded – within three time steps. After a rest period of two time steps, truck one arrives at its destination at $t = 9$. Truck two starts its tour by waiting one time step in order to synchronize with truck one, and truck two arrives at its final destination at $t = 8$.

4.3. Mathematical model for Stage 3

We propose a mixed-integer linear program that is defined on $G = (V, A)$. The sets of decision variables can be divided into two groups. The first group is defined on the arcs A: The binary decision variable x_{ak} is set to one if truck k uses arc $a \in A_K \cup A_I$. Since we assume that several platoons can travel simultaneously on the same highway, the integer decision variable y_{as} counts the number of platoons of size s that are traveling on arc $a \in A_P$. The binary decision variable z_{aks} is set to one if truck k is traveling in a platoon of size s on arc a and the binary decision variable w_{aks} is set to one if k leads a platoon of size s on arc a. The second group of decision variables is related to the driving time regulations. Since these variables capture the time, it is sufficient to define them on $\mathcal{V}$, the node set of the supporting network. So-called *clock variables*, keep track of the trucks' driving times by measuring the time after the last break or daily rest. u_{ik}^{in} is truck k's driving time since the last break after its arrival at node $i \in \mathcal{V}$, u_{ik}^{out} is the driving time when the truck leaves i. Similarly, v_{ik}^{in} and v_{ik}^{out} measure the driving time after the last daily rest. u_{ik}^{out} is reset

Figure 2 **Example of the iterinaries of two trucks in the time-space expanded two-layer network.**



when a truck takes a break or daily rest at i, while v_{ik}^{out} can only be reset after a daily break. To reset the breaks, the binary variables b_{ik} and r_{ik} indicate whether or not truck k takes a break or daily rest at node $i \in \mathcal{V}^W$. Table 1 gives an overview of the notation.

The total costs consist of the following three cost components:

(i) *fuel costs :=*

$$\sum_{k\in\mathcal{K}}\Big(\sum_{a\in A_K} c_{ak}^f \cdot x_{ak} + \sum_{a\in A_P}\sum_{s\in S}\big(c_{ak}^f \cdot \big(1-\eta^f \cdot \frac{(s-1)}{s}\big)\cdot z_{aks} + c_{ak}^f \cdot (1-\eta^l)\cdot w_{aks}\big)\Big).$$

When trucks platoon, the $s-1$ followers' fuel costs are reduced by η^f, whereas η^l reduces the leader's fuel expenses.

(ii) *personnel costs:=*

$$\sum_{k\in\mathcal{K}}\Big(\sum_{a\in A_K} c_{ak}^l \cdot x_{ak} + \sum_{a\in A_P}\sum_{s\in S}\big((1-\rho)\cdot c_{ak}^l \cdot z_{aks} + \rho\cdot c_{ak}^l \cdot w_{aks}\big)\Big) - \sum_{i\in\mathcal{V}^{\mathcal{W}}} c^w \cdot (B\cdot b_i + R\cdot r_i)\,.$$

If the rest-while-trailing option is allowed ($\rho > 0$), the follower's drivers have to be paid for $1-\rho$ of the driving time, whereas the driver of the leader has to be paid for the full time. Since we assume that drivers are not paid for mandatory breaks or rests, we subtract these costs.

(iii) *forming costs :=*

$$\sum_{k\in\mathcal{K}}\sum_{a\in A_I} c^p \cdot x_{ak}.$$

This term equals the costs for joining or leaving a platoon.

Table 1 Sets, parameters, functions and decision variables used in the model.

Sets, parameters and functions	
$V = V_K \cup V_P$	set of all time-expanded nodes, which can be partitioned into nodes on the truck level and platoon level
$\mathcal{V}$	set of nodes in the supporting network,
$\mathcal{V}^W$	set of way-point nodes in the supporting network
$A = A_K \cup A_I \cup A_P$	set of all arcs, which can be partitioned into truck arcs, interlayer arcs and platoon arcs
$\mathcal{K}$	set of all trucks
o_k, d_k	origin and destination of truck k
e_k, l_k	earliest departure at origin and latest arrival at destination of truck k
T	set of all time periods
t_{ij}	travel time between node i and node j
f, g	functions mapping $V \to \mathcal{V}$ and $V \to T$
ς	maximum size of a platoon
$S = \{2, \ldots, \varsigma\}$	set of all platoon sizes
c^f_{ak}, c^l_{ak}	fuel cost and labor cost of truck k on arc a
c^w, c^p	waiting cost, cost of joining or leaving a platoon
η^l, η^f	fuel reduction factor of platoon leader and platoon follower
ρ	rest-while-trailing factor
D^b, D^r	maximum driving time until next break or daily rest
B, R, D	duration of a break, daily rest or full day
Decision variables	
b_{ik}	if truck k takes a break at node i
r_{ik}	if truck k takes a daily rest at node i
u^{in}_{ik}	truck k's driving time after the last break or daily rest when entering node i
u^{out}_{ik}	truck k's driving time after the last break or daily rest when leaving node i
v^{in}_{ik}	truck k's driving time after the last daily rest when entering node i
v^{out}_{ik}	truck k's driving time after the last daily rest when leaving node i
w_{aks}	if trucks k leads a platoon of size s on arc a
x_{ak}	if truck k uses arc a
y_{as}	number of platoons of size s traveling on arc a
z_{aks}	if trucks k travels on arc a in a platoon of size s

The *Restricted Truck Platooning Planning Problem* (RTP) reads as follows:

$$\min \Big(fuel\ costs + personnel\ costs + forming\ costs \Big) \tag{1}$$

$$s.t. \quad \sum_{\substack{a \in A_K: \\ f(a^o) = o_k}} x_{ak} = 1 \qquad \forall k \in \mathcal{K} \tag{2}$$

$$\sum_{\substack{a \in A_K: \\ f(a^d) = d_k}} x_{ak} = 1 \qquad \forall k \in \mathcal{K} \tag{3}$$

$$\sum_{\substack{a \in A_K: \\ f(a^d)=i \wedge g(a^d)=t}} x_{ak} = \sum_{\substack{a \in A_K: \\ f(a^o)=i \wedge g(a^o)=t}} x_{ak} \qquad \forall k \in \mathcal{K}, i \in \mathcal{V}^W, t \in T \tag{4}$$

$$\sum_{s \in S} \sum_{\substack{a \in A_P: \\ f(a^o)=i \wedge g(a^o)=t}} z_{aks} = \sum_{\substack{a \in A_I^+: \\ f(a^o)=i \wedge g(a^o)=t}} x_{ak} \qquad \forall k \in \mathcal{K}, i \in \mathcal{V}^W, t \in T \tag{5}$$

$$\sum_{s \in S} \sum_{\substack{a \in A_P: \\ f(a^d)=j \wedge g(a^d)=t}} z_{aks} = \sum_{\substack{a \in A_I^-: \\ f(a^o)=j \wedge g(a^o)=t}} x_{ak} \qquad \forall k \in \mathcal{K}, j \in \mathcal{V}^W, t \in T \tag{6}$$

$$\sum_{k \in \mathcal{K}} z_{aks} = s \cdot y_{as} \qquad \forall a \in A_P, s \in S \tag{7}$$

$$\sum_{s \in S} \sum_{\substack{a \in A_P: \\ f(a^o)=i}} z_{aks} \leq 1 \qquad \forall i \in \mathcal{V}^W, k \in \mathcal{K} \tag{8}$$

In the objective function (1), we minimize the total costs, which are the sum of the fuel costs, personnel costs and forming costs. Equalities (2) and (3) ensure that each truck leaves its origin and enters its destination. Equality (4) conserves the flow for all other nodes in the truck layer. Hereby, the inflow and outflow can also originate from the platoon nodes via the interlayer arcs. Equations (5) and (6) state that when a truck uses an interlayer arc to or from a platoon node, the truck has to join or to leave a platoon at this waypoint. Since we assume that platoons offer a direct service between two nodes, platoons are disbanded as soon as they arrive at a waypoint. Nevertheless, trucks can join another platoon at the same waypoint in the same time step by choosing the corresponding interlayer arc. Constraint (7) relates the trucks to the number of platoons of size s that are traveling between two waypoint nodes. Constraint (8) states that each truck can only join one platoon at a waypoint.

$$\sum_{k \in \mathcal{K}} w_{aks} \geq y_{as} \qquad \forall a \in A_P, s \in S \tag{9}$$

$$z_{aks} \geq w_{aks} \qquad \forall a \in A_P, s \in S, k \in \mathcal{K} \tag{10}$$

$$x_{ak}, w_{aks}, z_{aks} \in \{0;1\}, \; y_{as} \in \mathbb{N}_0 \quad \forall a \in A, k \in \mathcal{K}, s \in S \tag{11}$$

Constraint (9) ensures that every platoon has one leader. This can be relaxed to an inequality since platoon leaders have higher costs than followers, which means that the optimal solution will always contain the minimal number of platoon leaders. Inequality (10) states that a truck can only lead a platoon if it is also part of the platoon.

4.4. Mathematical model for Stages 1 and 2

In this section, we introduce the constraints that allow us to extend *RTP-3* to *RTP-1* and *RTP-2*. The difference between the two stages lies in the rest-while-trailing factor ρ, with $\rho = 0$ in Stage 1 and $\rho \in (0;1]$ in Stage 2.

European driving time regulations: The following constraints formulate the European driving time regulations. Since the movements of the trucks are defined on the arcs of the time-expanded network, but the breaks and rests are related to the supporting network, we use the functions f and g to map the time-expanded nodes on the corresponding supporting nodes and time period, respectively.

$$u^{in}_{jk} \geq t_{ij} + u^{out}_{ik} - D^b \cdot (1 - x_{ak}) \quad \forall k \in \mathcal{K}, a \in A_K : f(a^o) = i, f(a^d) = j \in \mathcal{V} \tag{12}$$

$$u^{in}_{jk} \geq u^{out}_{ik} - D^b \cdot (1 - \sum_{s \in S} z_{aks}) + \tag{13}$$
$$t_{ij} \cdot \big(\rho \cdot \sum_{s \in S} w_{aks} + (1-\rho) \cdot \sum_{s \in S} z_{aks}\big) \; \forall k \in \mathcal{K}, a \in A_P : f(a^o) = i, f(a^d) = j \in \mathcal{V}$$

$$u^{out}_{jk} \geq u^{in}_{ik} - D^b \cdot (b_{ik} + r_{ik}) \quad \forall k \in \mathcal{K}, a \in A_K : f(a^o) = i, f(a^d) = j \in \mathcal{V} \tag{14}$$

Inequality (12) assures that the break clock is increased by the driving time if and only if a truck traverses an arc on the truck level. Similarly, constraint (13) increases the driving time for a truck that moves on the platoon level. If the rest-while-trailing option is activated by choosing $\rho > 0$, the incoming break clock increases for platoon followers by the share $1 - \rho$. If the truck is a platoon leader, the factor is increased to one by adding ρ. Whenever a truck takes a break or a rest, the outgoing break clock is reset by the logical constraint (14).

$$v^{in}_{jk} \geq t_{ij} + v^{out}_{ik} - D^r \cdot (1 - x_{ak}) \quad \forall k \in \mathcal{K}, a \in A_K : f(a^o) = i, f(a^d) = j \in \mathcal{V} \tag{15}$$

$$v^{in}_{jk} \geq v^{out}_{ik} - D^r \cdot (1 - \sum_{s \in S} z_{aks}) + \tag{16}$$
$$t_{ij} \cdot \big(\rho \cdot \sum_{s \in S} w_{aks} + (1-\rho) \cdot \sum_{s \in S} z_{aks}\big) \; \forall k \in \mathcal{K}, a \in A_P : f(a^o) = i, f(a^d) = j \in \mathcal{V}$$

$$v^{out}_{jk} \geq v^{in}_{ik} - D^r \cdot r_{ik} \quad \forall k \in \mathcal{K}, a \in A_K : f(a^o) = i, f(a^d) = j \in \mathcal{V} \tag{17}$$

$$D \geq v^{in}_{ik} + D^r \cdot r_{ik} \quad \forall k \in \mathcal{K}, i \in \mathcal{V} \tag{18}$$

Analogously to the previous three constraints, (15) and (16) increase the incoming rest clock variable and (17) resets the outgoing rest clock variable. Observe that v^{out}_{jk} is only reset after a daily rest. Inequality (18) states that a daily rest has to be taken 24 hours (D) after the last rest was taken.

$$1 \geq b_{ik} + r_{ik} \quad \forall i \in \mathcal{V}^W, k \in \mathcal{K} \tag{19}$$

$$D^b \geq u^{in}_{ik} \quad \forall i \in \mathcal{V}^W, k \in \mathcal{K} \tag{20}$$

$$D^r \geq v^{in}_{ik} \quad \forall i \in \mathcal{V}^W, k \in \mathcal{K} \tag{21}$$

$$\sum_{a \in A_K : f(a^o) = i \wedge f(a^d) = i} x_{ak} \geq B \cdot b_{ik} \quad \forall k \in \mathcal{K}, i \in \mathcal{V}^W \tag{22}$$

$$\sum_{a \in A_K : f(a^o) = i \wedge f(a^d) = i} x_{ak} \geq R \cdot r_{ik} \quad \forall k \in \mathcal{K}, i \in \mathcal{V}^W \tag{23}$$

$$b_{ik}, r_{ik} \in \{0; 1\}, \; u^{in}_{ik}, u^{out}_{ik}, v^{in}_{ik}, v^{out}_{ik} \in \mathbb{R}_0 \; \forall i \in \mathcal{V}, k \in \mathcal{K} \tag{24}$$

To preclude that breaks and daily rests are offset against each other, inequality (19) forbids that breaks and rests are taken at the same location. Constraints (20) and (21) limit the maximum driving time after the last break or rest period, respectively. The minimum duration of a break or daily rest is enforced by constraints (22) and (23), which requires trucks to "traverse" B or R waiting arcs, respectively. Due to the flow balancing equality (4), it is guaranteed that these waiting arcs are consecutive.

Canadian Commercial Vehicle Drivers Hours of Service Regulations: The RTP can be adapted to the *Commercial Vehicle Drivers Hours of Service Regulations* as follows:

- Set $R = 8$ h and $D^r = 13$ h for driving south of Latitude 60° North (and $D^r = 15$ h north of it). A second rest period has to be started 16 h (20 h), after the last one was completed. Since the duration of this rest is 8 h, we can set $D = 24$ h ($D = 28$ h).
- Since the Canadian regulations for breaks are different to the European ones, u_{ik}^{in} and u_{ik}^{out} are replaced by the continuous decision variables l_{ik}^{in}, l_{ik}^{out} and p_{ik}. l_{ik}^{in} and l_{ik}^{out} are *break clocks* that save the total break time that truck k has taken since the last rest when entering or leaving node i. p_{ik} measures the duration of the break that truck k takes at node i. $B^{max} = 2h$ measures the maximal required total time of breaks taken, B^{min} the minimal time that has to be taken per break.
- Constraints (12) - (14), (20) and (22) are replaced with the following constraints:

$$p_{ik} \leq \sum_{a \in A_K : f(a^o) = i \wedge f(a^d) = i} x_{ak} + t_{ij} \cdot \rho \cdot \sum_{s \in S} w_{aks} \quad \forall k \in \mathcal{K}, i \in \mathcal{V}^W, \quad a \in A_P : f(a^o) = i, f(a^d) = j \in \mathcal{V} \tag{25}$$

$$p_{ik} \geq B^{min} \cdot b_{ik} \quad \forall i \in \mathcal{V}^W, k \in \mathcal{K} \tag{26}$$

$$D \cdot b_{ik} \geq p_{ik} \quad \forall i \in \mathcal{V}^W, k \in \mathcal{K} \tag{27}$$

$$l_{ik}^{out} \geq l_{ik}^{in} - D \cdot r_{ik} \quad \forall k \in \mathcal{K}, i \in \mathcal{V} \tag{28}$$

$$l_{jk}^{in} \leq l_{ik}^{out} + p_{ik} + D \cdot (1 - x_{ak}) \quad \forall k \in \mathcal{K}, a \in A_K : f(a^o) = i, f(a^d) = j \in \mathcal{V} \tag{29}$$

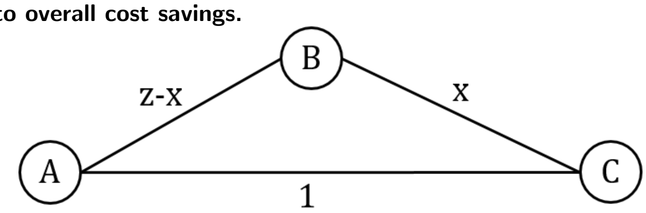
$$l_{jk}^{in} \leq l_{ik}^{out} + p_{ik} + D \cdot (1 - \sum_{s \in S} z_{aks}) \quad \forall k \in \mathcal{K}, a \in A_P : f(a^o) = i, f(a^d) = j \in \mathcal{V} \tag{30}$$

$$l_{ik}^{in} \geq B^{max} \cdot r_{ik} \quad \forall k \in \mathcal{K}, i \in \mathcal{V}^W \tag{31}$$

$$l_{ik}^{in}, l_{ik}^{out}, p_{ik} \in \mathbb{R}_0 \quad \forall i \in \mathcal{V}, k \in \mathcal{K} \tag{32}$$

(25) measures the duration of a break at a node. This also includes the time when traveling to a successor node as a platoon follower. Constraint (26) states that the duration of such a break has to be at least 30 minutes. Inequality (27) ensures that a break is only counted if a break is taken at the node. Due to (28), the outgoing break clock equals the incoming break clock

Figure 3 **Example of a detour that lies beyond the threshold defined by Larson, Munson, and Sokolov (2016) but still leads to overall cost savings.**



as long as no rest is taken at this node. If this is the case, the clock is reset. Constraints (29) and (30) transmit the values for the break clock between two consecutive nodes. Inequality (31) states that at least two hours of break need to be taken before a rest has been taken.

U.S. Hours of Service Regulations: When considering the *Hours of Service regulations* that hold in the United States, the problem relaxes to (1) - (10), (15) - (18), (21), (23) and (11) - (24) with $D^r = 11$ h, $R = 10$ h and $D = 24$ h.

4.5. Valid inequalities

We introduce the following two valid inequalities, which help to tighten the formulation:

$$\sum_{\substack{a \in A_K: \\ f(a^d)=i \wedge g(a^d)=t}} x_{ak} \leq \sum_{\substack{a \in A_K: \\ f(a^o)=i \wedge g(a^o)=t}} x_{ak} \qquad \forall k \in \mathcal{K}, i \in \mathcal{V}^W, t \in T \tag{33}$$

$$\sum_{\substack{a \in A_K: \\ f(a^o)=i \wedge f(a^d)=j}} x_{ak} + \sum_{s \in S} \sum_{\substack{a \in A_P: \\ f(a^o)=i \wedge f(a^d)=j}} z_{aks} \leq 1 \;\; \forall i, j \in \mathcal{V} : i \neq j, k \in \mathcal{K} \tag{34}$$

(33) states that a truck can only travel from a node after its arrival at this node. The second inequality (34) states that every truck can enter any physical node $j \in V$ at most once, either on the truck layer or on the platoon layer.

5. Pre-processing

To reduce the problem size of the RTP, we introduce a pre-processing procedure that, by exploiting the RTP's specific characteristics, only creates feasible arcs.

5.1. Bounded paths

In their Lemma 2.2, Larson, Munson, and Sokolov (2016) state that – when only considering the fuel cost – no truck is willing to drive more than $1 + \eta^f \cdot \frac{\varsigma - 1}{\varsigma}$ of its shortest path distance to join a platoon. However, this is only true if the total savings are not split afterwards, as Example 1 shows.

EXAMPLE 1 **(Detour optimum with platooning)**. *Consider two trucks traveling in the network given in Figure 3, where the triangle inequality holds. Truck 1 travels from* A *to* C*, while truck 2 goes from* B *to* C*. Let the distance between* A *and* C *be 1, and the path from* A *to* C *via* B *have length z. x denotes the distance between B and C, where the trucks are platooning. Furthermore, let be $\eta^l = 0$ and $c^l_{ak} = 0$. For simplicity, we assume $c^f_{ak} = 1$. If the trucks go individually, the total travel costs are $\gamma^{ind} = 1 + x$. If the trucks platoon between* B *and* C*, the total travel costs are $\gamma^{plt} = z + \left(1 - \eta^f\right) \cdot x$. Thus, the total savings are $\delta = \gamma^{ind} - \gamma^{plt} = 1 - z + \eta^f \cdot x$. Hence $x > \frac{z-1}{\eta^f} \Leftrightarrow \delta > 0$. Without loss of generality, truck 1 acts as platoon leader during the entire route, that is, has travel costs of z while truck 2 has costs of $\left(1 - \eta^f\right) \cdot x$. If the savings are equally split, truck 1 receives a payment of $\frac{1}{2} \cdot \left(-1 + z + \eta^f \cdot x\right)$, while truck 2 has to pay $\frac{1}{2} \cdot \left(1 - z + 3 \cdot \eta^f \cdot x\right)$. As a result, both trucks benefit from platooning as truck 1 pays $1 - \frac{\delta}{2}$ for its tour and truck 2 pays $x - \frac{\delta}{2}$.*

Example 1 shows that, even if $z > 1 + \frac{1}{2} \cdot \eta^f$, both trucks can reduce their travel cost as long as the platooning distance x is sufficiently long enough. As a consequence, the only bound that we can use, is the maximal traveling time of truck k, which is defined by $\theta_k := l_k - e_k$

To determine $\mathcal{P}^{\theta}_k$, the set of all θ_k-*bounded paths*, we use a search for every truck $k \in \mathcal{K}$ that relies on the bound θ_k. We initialize the search by determining $shortest_{i,d_k}$, all shortest paths from every node $i \in \mathcal{V} \backslash \{d_k\}$ in the supporting network to the truck's destination. $\mathcal{N}_i$ denotes all neighbors of node i and $\mathcal{N} = \bigcup_{i \in \mathcal{V} \backslash \{d_k\}} \mathcal{N}_i$ collects all neighbors. Information about the path are saved in the tuple $path = (path_1, path_2)$. $path_1$ is again a tuple that saves the order of the visited nodes. $path_2$ saves the current length of the path from o_k to $leaf$, which is the current last node of the path. All tuples $path$ are saved in the candidate set $\mathcal{C}$.

In the search, we select a candidate $path \in \mathcal{C}$ and explore all neighbors j of $leaf$. If the sum of the travel time to j plus $path_2$ plus the travel time from j to d_k is less or equal to θ_k, we update $path$ and select a new candidate. If $leaf = d_k$, we add $path_1$ to $\mathcal{P}^{\theta}_k$ and continue with the next candidate. The algorithm stops when $\mathcal{C}$ is empty. Algorithm 1 summarizes the search procedure, which can be accomplished in polynomial time as Lemma 1 shows.

Lemma 1 **(Polynomial runtime of Algorithm 1)**. *Algorithm 1 can be accomplished in* $\mathcal{O}\Big(|\mathcal{K}| \cdot \big(|\mathcal{A}| \cdot |\mathcal{V}| + |\mathcal{V}|^2 \cdot log(|\mathcal{V}|)\big)\Big)$.

Proof:

Computing all shortest paths from a node to d_k requires a runtime of $\mathcal{O}\Big(|\mathcal{V}| \cdot \big(|\mathcal{A}| + |\mathcal{V}| \cdot log(|\mathcal{V}|)\big)\Big)$. The selection of the candidates can be accomplished in $\mathcal{O}(|\mathcal{V}| + |\mathcal{A}|)$. Since the procedure has to be repeated for every truck, the total runtime is $\mathcal{O}\Big(|\mathcal{K}| \cdot \big(|\mathcal{A}| \cdot |\mathcal{V}| + |\mathcal{V}|^2 \cdot log(|\mathcal{V}|)\big)\Big)$. □

5.2. Feasible paths

When considering driving time regulations, the mandatory pauses extend the travel times on some paths $p \in \mathcal{P}^{\theta}_k$ to such extent that trucks violate their latest arrival l_k. Therefore, we exclude all those paths p, where mandatory break times and daily rests extend the travel times to such an extent

Algorithm 1 Bounded paths algorithm

Initialization: Compute $shortest_{i,d_k}$, $i \in \mathcal{V}\backslash\{d_k\}$, $\forall k \in \mathcal{K}$. Set $\mathcal{C} = \{\}$, $\mathcal{N} = \{\}$
for $k \in \mathcal{K}$ **do** $\mathcal{P}_k^\theta = \{\}$, $leaf = o_k$, $path = ((o_k), 0)$ $\mathcal{C} = \{path\}$,
  while $\mathcal{C} \neq \{\}$ **do**
    $\mathcal{C} = \mathcal{C}\backslash\{path\}$
    if $leaf = d_k$ **then** $\mathcal{P}_k^\theta = \mathcal{P}_k^\theta \cup path_1$
    else
      Determine all neighbors of $leaf$
      for $j \in \mathcal{V}\backslash\{path\}$: $\theta_k \geq t_{leaf,j} + path_2 + shortest_{j,d_k}$ **do**
        $\mathcal{N} = \mathcal{N}_{leaf} \cup \{j\}$
      end for
      Update candidate list
      for $i \in \mathcal{N}$ **do**
        $\mathcal{C} = ((path_1, i), path_2 + t_{leaf,j})$
      end for
    end if
    Select new candidate and set leaf: $path \in \mathcal{C}$, $leaf = path_1^{end}$
  end while
end for

that truck would arrive too late. We denote this set of driving-time-regulation-feasible paths, or simply *feasible paths* as $\mathcal{P}_k^f$. However, this is only true for Stage 1. Due to the rest-while-trailing option in Stage 2, trucks might not need to take a break or rest at all. Consequently, we cannot limit $\mathcal{P}_k^\theta$ to driving-time-regulation-feasible paths only.

5.3. Earliest arrival and latest departure

Having determined all bounded or feasible paths, for every truck we can determine its earliest arrival period and latest departure period at every node that is included in one of its feasible paths. We denote these values as $earliest_{ik}$ and $latest_{ik}$. Based on these values, we create the following arcs:

- **Truck arcs:**
  - —Moving arcs: if for any two nodes $i, j \in \mathcal{V}$ and time period $t \in T$ there exists at least one truck k such that $earliest_{ik} \leq t \leq latest_{jk} - t_{ij}$.
  - —Waiting arcs: if for any node $i \in \mathcal{V}$ and time period $t \in T$ there exists at least one truck k such that $earliest_{ik} \leq t \leq latest_{ik} - 1$.
- **Interlayer arcs**: if for any node $i \in \mathcal{V}$ and time period $t \in T$ there exist at least two trucks k and l such that $earliest_{ik} \leq t \leq latest_{ik}$ and $earliest_{il} \leq t \leq latest_{jl}$.
- **Platoon arcs**: if for any two nodes $i, j \in \mathcal{V}$ and time period $t \in T$ there exists at least one truck k such that $earliest_{ik} \leq t \leq latest_{ik} - t_{ij}$, $earliest_{jk} \leq t \leq latest_{jk} - t_{ij}$.

We denote these reduced arc sets as A'_K, A'_P and A'_I and their union as A'.

5.4. Fixing non-basic decision variables

For every truck k there may exist a subset of arcs in A' that cannot be traversed. Thus, we can set the following decision variables to zero:

- x_{ak}: if the travel-period lies beyond k's time window, i.e. $latest_{ik} < g(i)$ or $g(j) < earliest_{jk}$.
- w_{aks}, z_{aks}: if the travel-period lies beyond k's time window, i.e. $latest_{ik} < g(i)$ or $g(j) < earliest_{jk}$, $s \in S$.
- b_{ik}, r_{ik}: if node i is not included in any of k's feasible paths $p \in \mathcal{P}_k^f$.

5.5. Providing a starting solution

We know that an upper bound to the RTP is the total cost of all trucks driving individually on their shortest paths without platooning. Thus, we can provide an initial starting solution to the solver as follows: Let $short_k \subsetneq \mathcal{A}$ denote truck $k's$ shortest path in the network $\mathcal{V}$ and $short_k^{e_k} \subsetneq A_K$ the collection of arcs in the time-expanded network when starting at the earliest possible departure time e_k. By setting $x_{ak} = 1$ for all arcs $a \in short_k^{e_k}$ and all other decision variables to zero, we obtain a starting solution.

6. Computational study

The goal of this computational study is two-fold. First, we assess the computational performance of the solution approach as the RTP is solved in all three ACEA stages and we evaluate the corresponding optimal solutions. Moreover, we assess the *value of platooning* and the *value of autonomous driving*, given by the savings that can be achieved through combining platooning with the technology of autonomous driving. Hereby, we focus on the European driving time regulations as defined by constraints (12) - (24). Second, we conduct a sensitivity analysis to assess the impact of different platooning parameters and of the network structure on the optimal solution in Stage 3.

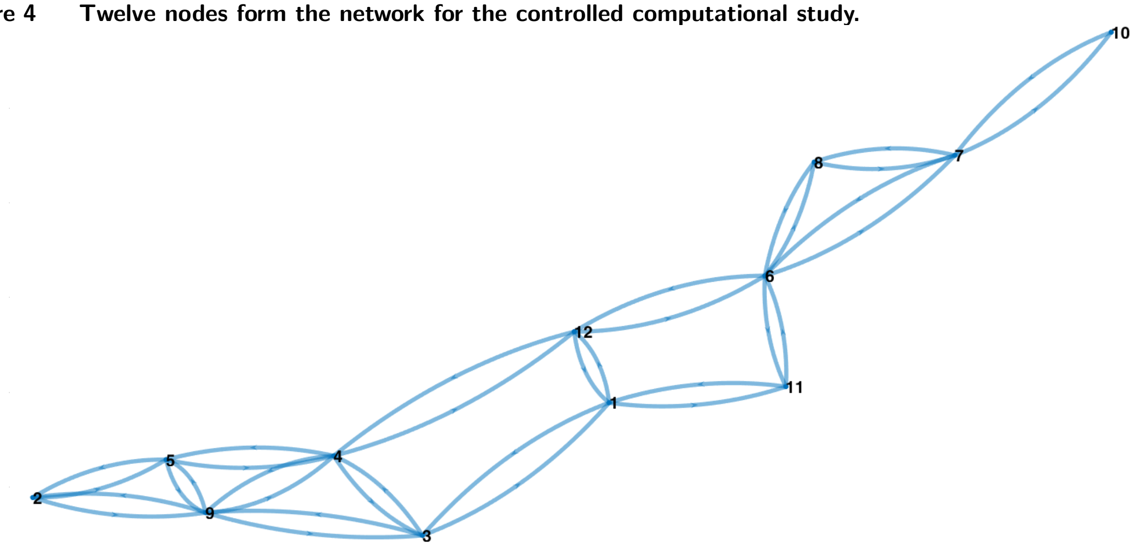
6.1. Key performance indicators

For the evaluation, we use the following key performance indicators:

- *Savings*: Relative changes in costs (total, fuel and personnel) for the optimal solution with the platooning option, as opposed to the costs of the optimal solution without the platooning option (that is, $\eta^f = 0$).
- *PER*: The *Platoon Exploitation Rate* (*PER*), which quantifies the share of the overall travel time in a platoon and is defined as follows:

$$PER := \frac{\sum_{k \in K} total\ time\ traveled\ by\ truck\ k\ in\ a\ platoon}{\sum_{k \in K} total\ time\ travelled\ by\ truck\ k} \ . \tag{35}$$

Figure 4 **Twelve nodes form the network for the controlled computational study.**



- TT_{diff}: Relative difference in the travel time, compared to the shortest path:

$$TT_{diff} := \frac{\sum_{k \in K} (travel\ time\ truck\ k - shortest\ path\ truck\ k)}{\sum_{k \in K} shortest\ path\ truck\ k} \,. \tag{36}$$

It measures the detours that trucks take in order to platoon with others.

- b_{diff}: relative difference in the number of breaks between the optimal solution with the platooning option and the optimal solution without the platooning option (that is, $\eta^f = 0$):

$$b_{diff} := \frac{no.\ of\ breaks\ with\ platooning - no.\ of\ breaks\ without\ platooning}{no.\ of\ breaks\ without\ platooning} \,. \tag{37}$$

- r_{diff}: relative difference in the number of rest periods between the optimal solution with the platooning option and the optimal solution without the platooning option (that is, $\eta^f = 0$):

$$r_{diff} := \frac{no.\ of\ rests\ with\ platooning - no.\ of\ rests\ without\ platooning}{no.\ of\ rests\ without\ platooning} \,. \tag{38}$$

b_{diff} and r_{diff} are used to see, how the number of breaks and rest periods that are taken changes if platooning (without and with the rest-while-trailing option) is allowed.

6.2. Experimental set-up

In the computational study, we use three different networks. The first one is a self-chosen network with 60 trucks and twelve nodes, which are depicted in Figure 4. We use this network to study the impact of driving time regulations on the central co-ordination of truck platoons.

The other two networks contain 150 trucks and 30 nodes each and are used to evaluate the computational performance for solving RTP-3 and for conducting a sensitivity analysis. The "Great Lakes network" one contains cities in the upper mid-east region of North America (Figure 7, Appendix). The "Ruhr network, Appendix" is formed out of 29 German cities in the west of Germany and Venlo, a Dutch border town (Figure 8). The differences in the two networks lie in the distances and in the shapes. The Great Lakes network has a total length of 27,432 km and contains 120 edges. It resembles a corridor, where the detour lengths are rather long. In contrast to that, the distances in the Ruhr network are shorter: the whole network contains 134 edges with a total length of 10,006 km. Thus, the average edge length in the Ruhr, 74.67 km, is three-times smaller than in the Great Lakes, where it lies at 228.60 km. Furthermore, the Ruhr network shows a grid-like structure with more possibilities for detours. This can be also seen from the number of arcs that were created during the pre-processing procedure, which we report in Table 3. The total, average number of arcs in the Ruhr is 6,355.25 and thus 16% higher than in the Great Lakes network with a total average number of 5,481 arcs.

In every network, the cities serve simultaneously as waypoint nodes. For the trucks, we assume that their origins and destinations are off the highway network. Therefore, we assign to every truck an entry and exit point in the highway network. In the following, we refer to these points as *entries* and *exits*.

The earliest possible start time is set equally for every truck k to $t=0$, whereas truck k's latest arrival time $late_k$ is calculated as

$$late_k(\varphi) = min\{(1+\varphi)\cdot earliest_k; latest_k\} \ , \tag{39}$$

where $earliest_k$ denotes the travel time on the shortest path and $latest_k$ the travel time on the longest path. Since we assume that trucks are driving individually on their first and last miles, these traveling times are randomly drawn from the interval $[45;90]$. Consequently, trucks arrive at different points in time at the highway nodes. Therefore, the random assignment of traveling times on the first mile and last mile can be interpreted as assigning different start times to the trucks.

For every network, we create 20 instances with randomly generated time windows as well as entries and exits. To reflect the real world situation, where the incoming and outgoing freight volumes of the cities are different, the random generation of the entries and exits in the Great Lakes network and the Ruhr network follow a multinomial distribution. We report the self-chosen probabilities in Table 12 (in the Appendix), which are based on the economic sizes of the cities.

In the self-chosen network and the Great Lakes network, the time is discretized into time steps with a length of 45 minutes. Consequently, we have to round the travel times to multiples of 45 minutes, which can lead to deviations by up to 22.5 minutes. Since the distances in the Ruhr network are smaller, we use time steps of 15 minutes. Consequently, the maximal deviation due to rounding lies at 7.5 minutes.

Table 2 Statistics for the pre-processing procedure on the self-chosen network.

	RTP-1			RTP-2			RTP-3		
	truck	platoon	time [sec]	truck	platoon	time [sec]	truck	platoon	time [sec]
Mean	3,127	861	12.05	8,352	2,728	21.35	5,378	1,516	16.50
Stdv	214	91	3.35	372	176	3.38	276	127	3.51
Max	3,501	1,065	26.13	9,465	3,163	24.91	5,887	1,689	22.03
Med	3,098	861	11.24	8,407	2,758	21.33	5,325	1,478	16.95
Min	2,684	700	9.42	7,594	2,182	18.80	4,679	1,264	9.48

The fuel cost is given by EUR 1.15 per liter (Statista 2018) and we base our calculations on an equal fuel consumption of 24 liters per hour. Thus, the fuel cost is EUR 20.70 per time-step. The personnel cost is fixed at EUR 30 per hour (Comite National Routier 2016) and therefore EUR 22.50 per time-step. Joining or leaving a platoon is assumed to have low costs. Therefore, we choose EUR 1 as cost.

To determine the value of platooning with autonomous driving, we limit the factorial design as follows: The platoon size limit is set to $\varsigma = 5$ and we assume that the platoon followers save $\eta^f = 15\%$ fuel, whereas the platoon leader enjoys no fuel savings ($\eta^l = 0\%$). The time windows are generated according to formula (39), setting $\varphi = 10\%$. For evaluating the computational performance when solving the RTP-3 on the Great Lakes network and the Ruhr network, the platoon followers' fuel savings factor and the maximal platoons size are varied as follows: $\eta^f \in \{5\%, 10\%, 15\%\}$ and $\varsigma \in \{3, 5\}$. Again, we choose $\eta^l = 0\%$ and $\varphi = 10\%$.

6.3. Computational performance of the pre-processing procedure

The pre-processing procedure is done with *MATLAB R2016b* on a Windows 10 PC with 4 Intel Core Xeon CPU (2.60 GHz) and 12 GB of RAM.

For the self-chosen network, we report the resulting number of arcs for every layer and the runtimes in Table 2. The smallest number of arcs is created for Stage 1, as driving time regulations allow to exclude several paths beforehand. The highest number of arcs is created for Stage 2, which is a result of the larger time windows due to the rest-while-trailing option (see Section 5). The arcs are created quickly, on average as few as 12 and up to 21 seconds. Observe that the duration of the shortest path and the longest path are shorter in Stage 3 since driving time regulations do not need to be considered. Due to the rest-while-trailing option in Stage 2, $earliest_k$ corresponds to the shortest path without driving time regulations and $latest_k$ corresponds to the path with driving time regulations. This results in more arcs that need to be created, since driving-time-infeasible paths cannot be removed if $\rho > 0$ (cf. Section 5).

In Table 3, we report the statistics of the pre-processing procedure on the two large networks. For the Great Lakes network, the average runtime lies at 22 seconds. In the Ruhr network, where the

Table 3 Statistics for the pre-processing procedure on the Great Lakes and the Ruhr network.

	Great Lakes			Ruhr		
	truck	platoon	time [sec]	truck	platoon	time [sec]
Mean	3,992	1,489	21.83	4,715	1,641	43.62
Stdv	214	118	0.78	147	81	3.44
Max	4,372	1,684	23.17	4,975	1,794	50.81
Med	3,989	1,510	21.93	4,709	1,644	43.54
Min	3,658	1,270	20.51	4,385	1,462	38.46

total average number of arcs created is 16% higher than for the Great Lakes network, the average runtime is 44 seconds, which is more than twice as high than for on the Great Lakes network. This is due to the fact that in the Ruhr network, there are more feasible paths that need to be evaluated by the procedure.

In total, the results show that the pre-processing procedure can produce the required arcs in a very short time.

6.4. Computational performance performance for solving the model

To solve the model, we use *FICO Xpress 8.6* on a Linux 4.4 server with 16 Intel Core Xeon CPU (2.60 GHz) and 72 GB of RAM. We consider a problem solved to optimality as soon as the optimality gap falls below 0.1%.

Table 4 summarizes the corresponding runtimes for solving the RTP for all three stages on the self-chosen network. As expected, the RTP-3 is the one that, with an average runtime of 17 minutes, takes the least time to solve, whereas the RTP requires more runtime. For RTP-1, the instances are solved on average within 53 minutes. For RTP-2, the runtime increases even further to an average of 75 minutes. This is caused by the larger input size due to more arcs and by the increased number of options due to the rest-while-trailing option.

Table 4 Runtimes (in seconds) for solving the RTP in all three stages on the self-chosen network.

	RTP-1	RTP-2	RTP-3
Mean	3,198	4,223	1,014
Stdv	1,816	1,675	506
Max	6,115	6,314	1,812
Med	2,368	4,523	1,075
Min	875	989	221

For the Great Lakes network and the Ruhr network, we report the results in Table 5: There are substantial differences between the runtimes on both networks. On the Great Lakes network, the runtimes vary between 8 and 18 minutes. Thereby, the main driver for longer computational

Table 5 Runtimes (in seconds) for solving RTP-3 on the Great Lakes network and the Ruhr network.

	Great Lakes network						Ruhr network					
	$\varsigma = 3$			$\varsigma = 5$			$\varsigma = 3$			$\varsigma = 5$		
η^f	5%	10%	15%	5%	10%	15%	5%	10%	15%	5%	10%	15%
Mean	469	1,012	1,124	426	788	1,028	1,035	2,484	3,130	813	859	1,313
Stdv	295	257	20	258	350	269	1,016	1,036	957	795	826	1,235
Max	1,147	1,150	1,167	1,176	1,188	1,202	4,035	4,077	4,063	4,233	4,112	4,191
Med	318	1,115	1,121	329	626	1,157	581	2,691	3,487	644	603	737
Min	238	362	1,087	254	334	406	409	596	714	422	366	393

times is the fuel savings factor η^f. This is caused by the fact that a higher η^f increases the number of detours that are still economical to drive and thus, more options need to be evaluated. The maximal platoon size ς, on the other hand, has no noticeable influence on the runtimes. Since the pre-processing procedure created more arcs for the Ruhr network (see Table 3), we observe longer runtimes on those instances. Here, the average runtimes lie between 14 and 53 minutes. What is of interest, is the fact that for $\varsigma = 5$, the average runtimes are lower than for $\varsigma = 3$. This is caused by symmetries in the solution, which occur when more than three trucks are platooning on the same arc. Then, more than one platoon has to be formed and every distribution of the trucks yields the same cost. Analogously to the Great Lakes network, a higher η^f increases the runtimes, since higher savings increase the number of detours with a positive fuel savings potential.

In sum, the results show that the runtimes are influenced by the network structure and platooning parameters.

6.5. Truck platooning in all three stages of automation

In the following, we analyze the optimal solutions to the RTP in all three stages. Table 6 summarizes the resulting KPIs.

Stage 1: In Stage 1, where all drivers have to be attentive (i.e., $\rho = 0\%$), the average total cost savings are 2.48%, with a maximum of 2.63% and a standard deviation of 0.11%. As Table 6 shows, these savings are a result of a lower fuel consumption; on average, 5.18% less fuel is burned if the trucks can platoon. The PER is rather low, namely in the range of 43.38% to 52.03% with a mean of 48.91%. The personnel costs do not change, although trucks might have to wait for others to form platoons. However, this waiting is counted as a break since drivers are not paid during these periods, whereas they receive wages when they have to wait additionally. Consequently, the number of breaks that are taken is on average 9.63% higher than without platooning, whereas the number of rest periods remains unchanged.

Table 6 **Cost savings, PER, TT_{diff}, b_{diff} and r_{diff} for solving the RTP with varying values of ρ.**

		Savings			PER	TT_{diff}	pauses	
		Total	Fuel	Pers			breaks	rests
RTP-1	Mean	2.48	5.18	0.00	48.91	0.00	9.63	0.00
	Stdv	0.11	0.23	0.00	1.76	0.00	8.75	0.00
	Max	2.63	5.62	0.00	52.03	0.00	28.23	0.00
	Med	2.48	5.23	0.00	48.22	0.00	10.74	0.00
	Min	2.27	4.71	0.00	43.38	0.00	0.00	0.00
RTP-2	Mean	30.08	7.55	71.02	72.03	1.20	9.19	-16.99
	Stdv	1.30	0.52	2.01	1.99	0.29	8.05	12.56
	Max	33.42	7.99	77.51	77.84	1.52	23.97	0.00
	Med	30.64	7.64	70.25	72.48	0.85	8.65	-15.87
	Min	28.70	6.11	68.91	69.10	0.23	-8.59	-36.80
RTP-3	Mean	8.75	8.75		73.15	0.09		
	Stdv	0.24	0.24		2.03	0.13		
	Max	9.59	9.59		76.69	0.53		
	Med	8.79	8.79		72.67	0.08		
	Min	8.41	8.41		69.31	0.00		

Stage 2: The rest-while-trailing option in Stage 2 leads to considerable cost savings. Moreover, in most of the cases, the rest-while-trailing option helps to reduce the number of rest periods taken. As Table 6 shows, on average 16.99% less rest periods are scheduled, compared to the case without platooning option. The total cost are by 30.08% lower than for the case without platooning (see Table 6). This is mainly due to the substantial reduction in the personnel cost of 71.02% on average. In addition, the fuel savings are higher than in Stage 1, with an average value of 7.55% . It needs to be mentioned that the average PER is 47% higher than in Stage 1. However, the average fuel savings are 45% higher. The reason for this lower number is the fact that the average deviation from the shortest path is 1.20%, with a maximum of 1.52%. This shows that trucks drive detours to reduce more personnel cost, since the savings in wages exceed the additional fuel expenses.

Stage 3: All trucks drive autonomously and since there are no drivers, no driving time regulations need to be considered, neither wages need to be paid. Consequently, only the fuel savings influence the decision on the routing and scheduling of the trucks. As Table 6 shows, the platooning option leads to average fuel cost savings of 8.75% and a mean PER of 73.15%. The reason why the fuel savings are higher than in Stage 2 while the average PER remains almost unchanged (72.03%) is that less detours are driven. The mean difference in travel times is 0.09%. This is due to the fact that the trucks are unmanned and thus cannot exploit personnel cost savings like in Stage 2. Thus, similar to Stage 1, the trucks do mostly stay on their shortest paths since the additional fuel expenses for detours exceed the savings.

The value of platooning and autonomous driving: The main benefit of truck platooning is a reduced fuel consumption. From Table 6, we can deduce that the average *value of truck platooning* lies at 5.18%. It is also of interest to determine the effect of a higher degree of automation. That is, the change in the fuel savings in Stages 2 and 3, compared to the status quo Stage 1. We denote this the *value of autonomous driving*, which is 2.45% for Stage 2 and 3.57% for Stage 3.

In 2017, the total number of tonne-kilometers (tkm) driven in the 28 countries of the European Union were 1,913 billion (Eurostat 2017). Assuming that all trucks that drove more than 150 km were using motorways, this number reduces to 1,488 billion tkm (Eurostat 2017). The average fuel consumption of a truck in Europe lied at this time around 2.9 liters/tkm (Statistisches Bundesamt 2018), the average CO_2 emissions around 61 g/tkm (Institut für Energie- und Umweltforschung Heidelberg GmbH 2014). Based on these assumptions, trucks burned 4,318 billion liters of fuel on motorways in 2017, while emitting 90 million tons of CO_2. Thus, truck platooning could have saved approximately 224 billion liters of fuel on European motorways in 2017. This corresponds to 4.70 million tons less CO_2 emissions, which is 0.51% of the total transportation emissions in the European Union in 2016 (European Commission 2018). If the trucks would have been driving in Stage 2, the savings would further increase on average to 326 billion liters less fuel and 6.86 million tons less CO_2 emissions, whereas these values would reach in the third Stage 378 billion liters and 7.95 million tons. That is, autonomously driving platoons would have reduced the total transportation emissions in the European Union by 0.85%. Although these numbers represent an estimate, they show the scale of the fuel and CO_2 emissions savings potential through truck platooning in combination with autonomous driving.

6.6. Sensitivity analysis for Stage 3

The sensitivity analysis consists of three parts. First, we examine the influence of the platoon followers' fuel-savings factor and the maximal platoon size. Second, we vary the trucks' buffer times by increasing φ in formula (39). Third, we study the case when the platoon leader saves fuel as well.

Varying the fuel-savings and maximal platoon size: In Table 7, we display the relative fuel savings achieved by platooning and the PER. The average fuel savings lie in the range of 2.13% to 7.44%. As one can see, the main driver for the fuel savings is η^f, whereas the platoon size limit ς has a smaller effect. The average PER lies in the range of 70% and there are only small differences between the cases: the maximum difference between the average PER's lies at 1.03 percentage points. This nearly constant PER results from the fact that the trucks almost never do a detour to platoon with other trucks. This can be seen from the small deviations in the travel times in Table 8. In the maximum, the travel times are 0.12% longer than without platooning.

Table 7 Relative fuel savings and PER in the Great Lakes network.

	Fuel savings [%]						PER [%]					
	$\varsigma = 3$			$\varsigma = 5$			$\varsigma = 3$			$\varsigma = 5$		
η^f	5%	10%	15%	5%	10%	15%	5%	10%	15%	5%	10%	15%
Mean	2.13	4.30	6.49	2.44	4.94	7.44	69.26	69.66	70.11	69.47	70.10	70.39
Stdv	0.08	0.17	0.26	0.10	0.19	0.28	2.44	2.63	2.49	2.42	2.31	2.14
Max	2.28	4.59	6.94	2.65	5.38	8.09	73.42	74.19	74.93	74.02	74.99	74.48
Med	2.14	4.33	6.54	2.44	4.96	7.47	69.53	69.94	69.88	69.88	69.99	70.34
Min	1.98	3.98	6.03	2.25	4.58	6.89	64.92	64.98	66.03	65.96	66.82	67.46

Table 8 Relative travel time difference TT_{diff} and waiting per truck (in time steps) in the Great Lakes network.

	TT_{diff} [%]						Waiting [time steps]					
	$\varsigma = 3$			$\varsigma = 5$			$\varsigma = 3$			$\varsigma = 5$		
η^f	5%	10%	15%	5%	10%	15%	5%	10%	15%	5%	10%	15%
Mean	0.00	0.01	0.04	0.00	0.01	0.03	2.69	3.32	3.67	2.31	2.75	2.80
Stdv	0.00	0.02	0.04	0.00	0.02	0.04	1.06	1.02	1.44	0.78	0.85	1.00
Max	0.00	0.05	0.12	0.00	0.04	0.12	5.47	6.13	8.40	4.00	5.33	4.53
Med	0.00	0.00	0.04	0.00	0.00	0.04	2.67	3.27	3.60	2.40	2.67	2.87
Min	0.00	0.00	0.00	0.00	0.00	0.00	0.93	2.13	1.60	1.07	0.93	0.93

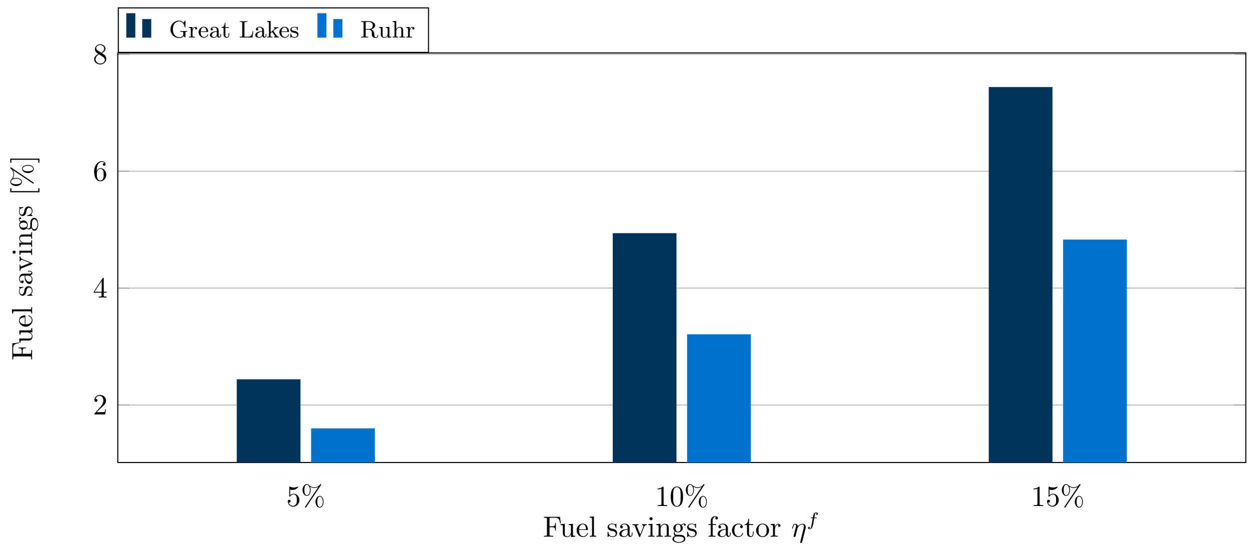
Table 9 Relative fuel savings, PER, relative travel time difference TT_{diff} and waiting times (in time-steps) in the Ruhr network.

	Fuel savings [%]			PER [%]			TT_{diff} [%]			Waiting		
η^f	5%	10%	15%	5%	10%	15%	5%	10%	15%	5%	10%	15%
Mean	1.60	3.21	4.83	47.37	47.59	48.06	0.00	0.01	0.06	0.37	0.99	1.52
Stdv	0.06	0.13	0.19	1.58	1.45	1.71	0.00	0.02	0.03	0.24	0.34	0.51
Max	1.71	3.43	5.16	49.91	50.05	51.87	0.00	0.07	0.14	0.80	1.47	2.67
Med	1.58	3.17	4.77	47.25	47.44	47.80	0.00	0.00	0.05	0.40	1.20	1.53
Min	1.46	2.94	4.43	44.31	44.49	44.51	0.00	0.00	0.00	0.00	0.01	0.03

This indicates that the expenses for a detour exceed the fuel savings. Thus, the modest increase in the PER origins from the fact that for a higher η^f, the fuel-savings exceed the cost of waiting. Therefore, the waiting times increase with a higher η^f (see Table 8). A larger ς allows more trucks to exploit a reduced air drag and thus to achieve higher fuel savings. Therefore, we observe higher fuel savings for $\varsigma = 5$.

Concluding, the results demonstrate that trucks do rarely deviate from their shortest paths. An explanation to this observation can be the shape of the Great Lakes network, which offers limited possibilities to drive a detour. Therefore, we solve the RTP on the Ruhr network, where the distances are shorter and more detour options are given. Hereby, we limit the factorial design to $\varsigma = 5$.

Figure 5 **Average fuel savings achieved through platooning in the Great Lakes network and in the Ruhr network ($\varphi = 10\%$, $\varsigma = 5$).**



In Table 9, we report the results for the Ruhr network. The average fuel-savings that are achieved lie between 1.60% and 4.83%, which is considerably lower than in the Great Lakes network. Figure 5 visualizes this by displaying the average fuel savings that were achieved in the two networks with $\varsigma = 5$. The average PER, reported in Table 9, lies between 47.37% and 48.06%, which is substantially lower than in the Great Lakes network with values of 69.47% and 70.39%. This shows that less distances are covered in platoons.

As one can see from TT_{diff}, the deviations from the shortest paths are twice as high as in the Great Lakes network, but still marginal. Hence, also in the Ruhr network, trucks stick mostly to their shortest paths and since the network contains more edges, less truck paths do overlap. Therefore, the PER and consequently the fuel-savings are lower than in the Great Lakes network.

Varying the buffer time: So far, we fixed the trucks' time slack with $\varphi = 10\%$. To see how the buffer times influence the optimal solution, we vary $\varphi \in \{0\%, 10\%, 20\%\}$. Hereby, the fuel savings factor is set to $\eta^f = 10\%$ and the platoon size limit to $\varsigma = 5$. We report the resulting KPIs in Table 10, which shows that the buffer time has a significant impact on the fuel savings. When granting no slack, the average fuel savings are 3.63% whereas the PER lies at 54.41% (cf. Table 10).

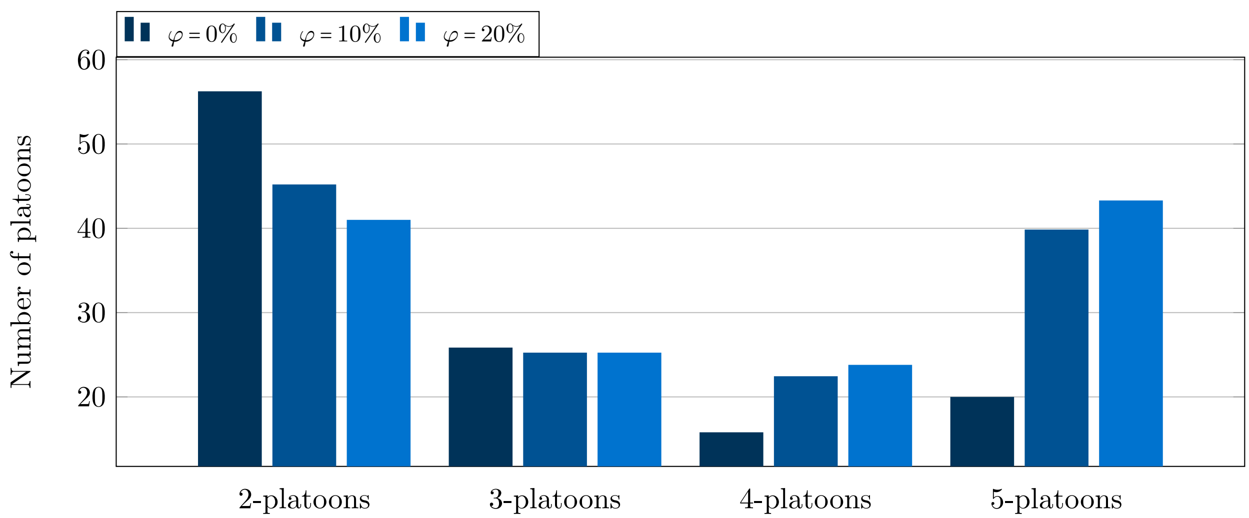
When increasing φ to 20%, the average fuel savings are 5.17%. Simultaneously, we can observe a higher PER of 72.60%. However, a larger buffer does not lead to more detours driven: for $\varphi = 20\%$ and $\varphi = 10\%$, the quartiles of TT_{diff} are identical and those deviations are very small, lying in the order of 0.01 percentage points. From that we conclude that the buffer time is not spent for driving longer detours. Instead, the additional time is spent for waiting for other trucks to form larger platoons along the shortest paths. Therefore, the average waiting time is more than twice as high

Table 10 Relative fuel savings, PER, relative travel time difference TT_{diff} and waiting times (in time steps) for varying buffer time φ.

	Fuel savings [%]			PER [%]			TT_{diff} [%]			Waiting		
φ	0%	10%	20%	0%	10%	20%	0%	10%	20%	0%	10%	20%
Mean	3.63	4.94	5.17	54.41	70.10	72.60	0.00	0.01	0.01	0	412	830
Stdv	0.28	0.19	0.18	3.30	2.31	2.09	0.00	0.02	0.02	0	128	301
Max	4.08	5.38	5.55	60.08	74.99	77.01	0.00	0.04	0.04	0	800	1,300
Med	3.65	4.96	5.14	54.67	69.99	72.34	0.00	0.00	0.00	0	400	890
Min	3.06	4.58	4.90	48.10	66.82	69.28	0.00	0.00	0.00	0	140	340

for $\varphi = 20\%$, compared to $\varphi = 10\%$ (see Table 10). The grater the buffer time, the larger platoons are formed. This can bee seen from Figure 6, that shows the average numbers of platoons of size $s \in \{2,...,5\}$ that were formed.

Figure 6 Average number of platoons of size s that are formed under varying buffer time in the Great Lakes network.



To conclude, larger buffer times are not exploited to drive longer detours but to wait for other trucks to form larger platoons. This allows for higher fuel savings.

Fuel-savings for the platoon leader: According to Tsugawa, Kato, and Aoki (2011), the platoon leader can reduce its fuel consumption by up to 7.5% due to reduced vortexes. In the following, we set $\eta^l = 5\%$, $\eta^f = 10\%$, $\varphi = 10\%$ and vary $\varsigma \in \{3,5\}$. Table 11 summarizes the results. It shows that the average fuel-savings lie at 5.70% and 6.02%. These values are, compared to the case of $\eta^l = 0\%$, obviously higher since the fuel-savings potential of the whole platoon increases. However, a part of the increase in the savings stems from a slightly higher PER; the average values go up by two percentage points to 71.62% and 71.80%. This is a result of slightly more detours

Table 11 **Relative fuel savings, PER, relative travel time difference TT_{diff} and total number of platoons that were formed for $\eta^l = 5\%$, $\eta^f = 10\%$ and $\varphi = 10\%$ in the Great Lakes network.**

	Savings [%]		PER [%]		TT_{diff} [%]		Platoons	
ς	3	5	3	5	3	5	3	5
Mean	5.70	6.02	71.69	71.80	0.03	0.03	183	145
Stdv	0.20	0.20	2.22	2.12	0.03	0.04	11	8.26
Max	6.09	6.41	76.14	75.87	0.12	0.17	204	161
Med	5.73	6.02	71.51	72.04	0.00	0.00	186	146
Min	5.37	5.70	68.33	68.05	0.00	0.00	164	125

that are driven. This can be seen from the average TT_{diff} which is three times higher than in the basic case with $\eta^l = 0\%$. What is of interest is the fact that the maximum deviation lies at 0.12% and 0.17%, respectively. These results indicate that with sufficiently high fuel-savings, trucks are willing to drive more and longer detours.

7. Conclusion

Truck platooning represents a bridging technology towards the wide spread usage of autonomously driving trucks. In this paper, we focused on the central planning of truck platoons through a multi-brand platform and proposed a methodology that is appropriate for all three stages of autonomous driving, defined by the *European Automobile Manufacturers' Association*. Since this planning has to be done with some lead time, we studied the day-before truck platooning planning problem. Due to the fact that trucks cover long distances, we took driving time regulations into consideration. By including the option to rest-while-trailing, we modeled the case where only the driver of the leading truck needs to be fully attentive, whereas the drivers of the following trucks can perform other tasks or rest.

The results of our computational study show that truck platooning offers a big potential to reduce fuel-consumption and CO_2 emissions in all three stages. Driving time regulations have large impact in the planning as they reduce the savings potential through platooning by up to two thirds of its value. This is mainly a result of rest periods that need to be taken and thus reduce the trucks' flexibility to synchronize with other trucks. Thus, it is important to consider mandatory break and rest periods in the routing and scheduling of truck platoons. However, breaks can be scheduled in such way that they are used as waiting times for other trucks. Therefore, the fuel savings potential is still remarkable. In Stage 2, the total cost savings considerably increase due to the rest-while-trailing option. Therefore, trucks might drive detours in a platoon to save personnel cost. In Stages 1 and 3, where only fuel costs can be saved, the trucks mostly stay on their shortest paths. In these cases, the main challenge when solving the problem is to schedule the trucks' departures and waiting times in such way that the trucks can platoon on their shortest paths. Furthermore, we could see that networks with a corridor-like structure foster the formation of platoons as more trucks share their shortest paths.

Due to the large overlaps between the Canadian and the European regulations, we expect similar results under the Canadian Commercial Vehicle Drivers Hours of Service Regulations. In the United States, where the Hours of Service regulations do not include mandatory breaks, the drivers have to take voluntary pauses to synchronize with other trucks and thus the waiting cannot be absorbed into breaks. However, the option to rest-while-trailing might allow the drivers to prolong their tours to up to 14 hours of daily driving time.

A technology that might substantially change the long-haul trucking industry are battery electric trucks (Earl et al. 2018). Since the recharging of these trucks will take considerably more time than refueling conventional trucks, transportation costs will probably increase due to higher idle times. Truck platooning can help with the reduction of the number of rechargings required for battery electric trucks since less energy is consumed and thus greater distances can be covered. Consequently, it is worth to further investigate truck platooning with battery electric trucks.

Summarizing, we studied the planning problem for truck platoons under driving time regulations, proposed a novel mathematical formulation and a pre-processing method and evaluated our model. Our methodological contribution goes well beyond truck platooning and can find application in the general field of consolidation-based transportation.

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Appendix A: Networks

Table 12 Probabilities (Prob.) for the multinomial sampling of entries and exits out of 30 cities in the regions of the Great Lakes and of the Ruhr.

Region	City	Prob.	City	Prob.	City	Prob.
Great Lakes	Albany	0.01	Grayling	0.01	Ottawa	0.03
	Buffalo	0.03	Green Bay	0.03	Québec	0.02
	Burlington	0.01	Indianapolis	0.10	Sault Saint Marie	0.02
	Chicago	0.15	Kalamazoo	0.01	Sherbrooke	0.02
	Cleveland	0.02	Kingston	0.01	Sudbury	0.01
	Columbus	0.05	Madison	0.03	Syracuse	0.01
	Detroit	0.11	Milwaukee	0.03	Toledo	0.01
	Flint	0.01	Montréal	0.10	Toronto	0.10
	Fort Wayne	0.01	North Bay	0.01	Trois-Rivières	0.02
	Gladstone	0.01	Orillia	0.01	White Oak	0.01
Ruhr	Aachen	0.05	Düsseldorf	0.06	Leverkusen	0.03
	Bad Hersfeld	0.10	Essen	0.01	Mainz	0.02
	Bad Wünnenberg	0.02	Frankfurt	0.10	Minden	0.04
	Bielefeld	0.05	Gießen	0.01	Mönchengladbach	0.01
	Bingen	0.01	Göttingen	0.01	Münster	0.01
	Bochum	0.02	Hagen	0.02	Osnabrück	0.03
	Bonn	0.03	Hannover	0.05	Salzgitter	0.04
	Braunschweig	0.02	Kassel	0.01	Siegen	0.01
	Dortmund	0.05	Koblenz	0.01	Venlo	0.09
	Duisburg	0.07	Köln	0.01	Wuppertal	0.01

Figure 7 Thirty cities in the area of the Great Lakes (Canada and U.S.).

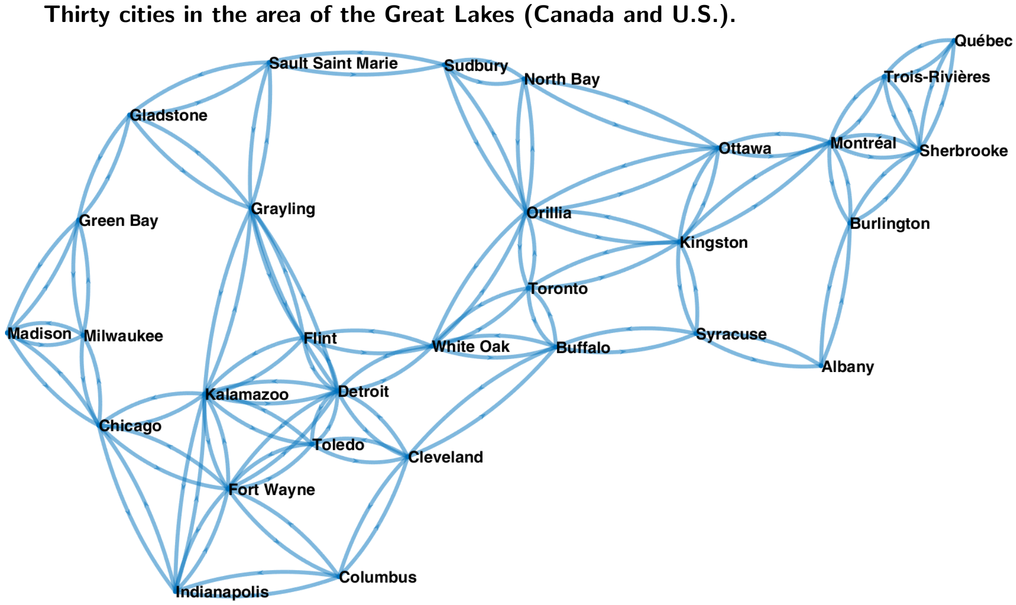

Figure 8 Thirty cities in the region of the Ruhr.