

Planning of Truck Platoons: a Literature Review and Directions for Future Research

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Abstract

A truck platoon is a set of virtually linked trucks that drive closely behind one another using automated driving technology. Benefits of truck platooning include cost savings, reduced emissions, and more efficient use of road capacity. To fully reap these benefits in the initial phases of technology deployment, careful planning of platoons based on trucks' itineraries and time schedules is required. This paper provides a framework to classify various new transportation planning problems that arise in truck platooning, surveys relevant operations research models for these problems in the literature and identifies directions for future research.

Keywords: Truck platooning, Optimization, Transportation, Automated driving, Review paper

1. Introduction

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

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leading truck.

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

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

Automated driving has been successfully deployed in closed environments in various
logistics and freight transportation settings such as port terminals (Kim and Bae, 2004) and
25 warehouses and factories (Azadeh et al., 2017; Roodbergen and Vis, 2009). Truck platooning
can be considered as a first step towards automated freight transportation in an open and
uncontrolled environment. Given the development of automated driving technology, we
expect to see the driving task become less dependent on humans i.e. in the future, not all
trucks in a platoon would require drivers (Kilcarr, 2016).

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

35 When a sufficient number of vehicles are capable of platooning, it is likely that platoons
can be spontaneously formed without planning in advance. However, in the initial stages,
when the deployment of platooning technology is not widespread or on routes with little

freight traffic, careful centralized planning is required to create platoons (Janssen et al., 2015). A so-called platooning service provider (Roland Berger, 2016; Janssen et al., 2015) could organize the planning and control of platoons between different fleets. Platoons could be scheduled in advance or planned in real-time during execution.

To establish a platoon, the departure times, travel speeds and the routes of the trucks in the platoon must be synchronized. A truck may, for instance, adjust its route and possibly even make a small detour to join a platoon. Figure 1 depicts an example of a platoon between two trucks in which one of the trucks makes a detour to form the platoon.

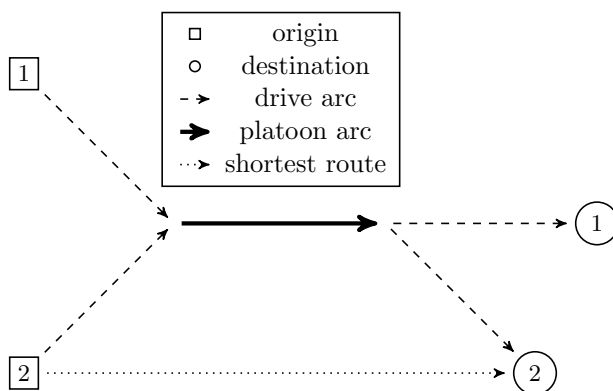


Figure 1: A two-truck platoon

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

This paper aims to fill the above mentioned gap by classifying the different planning problems that arise in truck platooning, reviewing the emerging literature related to this planning and identifying directions for future research. More specifically, the goal of this

paper is fourfold: (1) provide a systematic overview of different forms of platooning; (2)
60 identify and define relevant planning problems to support the different forms of platooning;
(3) provide an overview of relevant operations research models and approaches for these
problems in the literature and; (4) identify gaps and areas for future research.

This paper focuses on truck platooning but similar issues may arise in the planning of
platoons of regular cars and other vehicles not only on the road but also on water (see Lauf
65 (2017); TU Delft 3mE (2017)) and in air (see Chen et al. (2015); Richert and Cortés (2012)).

The paper is structured as follows. Section 2 explains the main characteristics of pla-
tooning planning. In Section 3, we compare platooning with other collaborative transport
systems such as ride-sharing and freight consolidation. Section 4 describes different platoon
settings and related static planning problems from the literature. Section 5 discusses plan-
70 ning problems that arise when technology and legislation allow platoons with (partially)
driverless trucks. Section 6 discusses the planning of platoons in real-time. Section 7 looks
at vehicle routing with platooning. The effects of platooning on network design are discussed
in Section 8. Finally, Section 9 identifies some future research opportunities and concludes
the paper.

75 **2. Characteristics of truck platoon planning**

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

80 *2.1. Platoon planning process and dynamics*

To explain the planning processes, we consider a platooning service provider that creates
platoon plans based on the trip information from different trucks. Each trip announcement
specifies an origin location, a destination location, an earliest departure time, and a latest
arrival time at the destination. We assume that there is typically some flexibility in the
85 departure time, i.e. it is not necessary to leave at the earliest departure time to arrive at
the destination before the latest arrival time. Moreover, there may be different possible

routes between the origin and the destination. The trip announcement also specifies the characteristics of the truck and its load and could contain preferences for the position within the platoon.

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

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

Scheduled platoon planning All trips are announced before the start of the operations.

Therefore, all platoon plans can be created in advance. This is often referred to as off-line or static planning.

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

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

When the deployment of platooning technology is not widespread, opportunistic platooning will not be very successful in creating platoons and therefore some form of planning is required. A simulation study by Liang et al. (2014) shows that there are substantial benefits associated with the careful planning of platoons. In the subsequent sections of the paper, we

115 first discuss various aspects of scheduled platoon planning and then highlight the additional challenges in real-time platoon planning.

2.2. Platooning objectives

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

120 Minimize the system-wide fuel cost

This objective aims to minimize the total fuel cost of all trucks in the system. To determine the net costs of a platoon, one should not only consider the fuel savings that occur within the platoon but also the additional fuel consumed to create the platoon due to detours or speed changes to catch up with a truck. Using a fuel consumption model, Liang et al. (2013) conclude that a platoon is beneficial only if the platooning distance is much larger than the catch-up distance. The minimization of the fuel costs would initially be one of the main operational benefit of platooning for individual truck operators.

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

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

Maximize the number of trucks in a platoon

140 Instead of minimizing the system-wide fuel cost, a platoon service provider could also maximize the number of matched trucks in the system. The increased likelihood of finding a platoon may be an important criterion to keep truck companies involved. Furthermore,

involving more companies by creating more matches in the initial stages of technology deployment could help spread confidence and trust in the system. The higher matching rate could consequently stimulate larger participant pools by attracting more truck companies in the future. Moreover, the possibly higher number of platoons created as a result of this objective may help gain more experience with automatic driving and platooning which could prove to be invaluable for the future success of the system. Note that this objective could potentially conflict with the previously described objective of minimizing the fuel costs.

2.3. Constraints on platoon formation

Various prerequisites determine whether it is feasible to form a platoon between a set of trucks. One of the most important constraints is the timing of the trips. Since freight transportation typically operates within tight time windows that are specified by the customers, there may be only little flexibility to wait for another truck to form a platoon. Instead of hard constraints on the time windows, table 1 shows that some studies consider soft time constraints by penalizing delays.

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

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

It is likely that there will be legal limitations on the length of the platoon (Eckhardt et al., 2016). This is to prevent long platoons disturbing the traffic flow by making it difficult for other vehicles to merge onto highways. Additionally, long platoons could lead to increased wear and tear of roads and bridges since such infrastructure has not been designed for dense truck platoons. Also, the required communication technology for platooning may not be very reliable in tunnels. As a result, it may become necessary to construct dedicated

infrastructure for platoon traffic. This type of routing constraints are considered in the area of convoy planning (see Tuson and Harrison (2005); Kumar and Narendran (2010); Tuson and Harrison (2005); Chardaire et al. (2005) for an example).

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

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

Table 1 provides an overview of the different objectives, constraints, and the decision variables that are used in the platooning literature.

2.4. Dividing the benefits of platooning

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

With scheduled truck platoons, simple proportional rules may be an appropriate way to divide the total system-wide benefits. However, this becomes difficult in a dynamic setting in which trucks can join and leave a platoon at any time. This is related to the division of shared
200 benefits in multi-passenger ride-sharing (Furuhata et al., 2013). This issue is related to the

stream of literature on inter-organizational collaboration (Cruijssen et al., 2007). Much of the research in this area makes use of cooperative game theory which considers scenarios where different parties form alliances that aim to achieve some goals jointly in an attempt to increase their individual profits (see Elkind and Rothe (2016) for more information).

205 Cooperative game theory has been extensively applied to solve various benefit allocation problems in the area of logistics. For examples of applications, see Lozano et al. (2013); Frisk et al. (2010); Krajewska et al. (2008). For a review of studies, see Guajardo and Rönnqvist (2016).

If the same trucks regularly platoon together as in a coalition, they could share the 210 benefits by taking turns as leading truck. Richert and Cortés (2012) propose a similar idea in the context of unmanned aerial vehicles (UAVs). This is also comparable to carpool schemes in which different participants act as driver each time, e.g., Fagin and Williams (1983) propose scheduling algorithms to determine which carpool participant should drive in each carpool to fairly divide the workload. Likewise, one could assign the more beneficial 215 following positions to the truck that incurs most costs to join the platoon.

Another consideration in the centralized planning of platoons is that system-optimal solutions are not necessarily optimal for each of the individual participants. A solution is not ‘stable’ if there exist pairs of trucks that are better off forming a platoon together than with the system assigned platoon partners. Wang et al. (2017) consider this in the context 220 of dynamic ride-sharing.

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

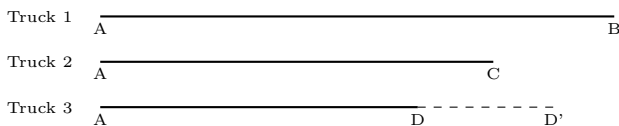


Figure 2: Example of strategic behaviour by truck 3

A simple example is shown in figure 2. Here, trucks 1,2, and 3 need to travel from A to 225 B, C, and D respectively. The system-optimal solution would entail a platoon with trucks

Table 1: Overview of platoon planning literature

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

PC - platoon composition, R - route, S - schedule, SC - speed changes

¹ - studies without a speed constraint assume a fixed driving speed

1 and 2 since the overlap in their routes is the longest. Knowing this, truck 3 could falsely report his destination as D' resulting in a platoon with trucks 1 and 3. Clearly, this isn't the system-optimal solution any more.

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

3. Comparison with other collaborative transportation systems

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

between platooning and freight consolidation and ride-sharing.

3.1. Freight consolidation

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

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

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

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

3.2. Ride-sharing

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

consolidation is that people are less flexible than load specially with respect to travel and waiting times.

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

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

Truck platooning and ride-sharing may result in less fuel consumption and consequently, reduced emissions. They involve matching entities with similar routes and time schedules. Both of them operate under certain capacity constraints. For ride-sharing, the capacity is associated with the number of seats in the car. For platoons, the length of a platoon is
285 conceptually unlimited but will likely be restricted by legislation. Also like in platooning, drivers part of ride-sharing services are likely to have to make some detours or adjust their time schedules to pick up riders.

Ride-sharing has recently started to receive much attention in literature. Furuhata et al. (2013) and Agatz et al. (2012) provide reviews of the different studies and the various solution
290 methodologies in ride-sharing literature. Similar concepts have also been applied to freight (see Arslan et al. (2016)). Table 2 summarizes the comparison between platooning, ride-sharing and freight consolidation.

Table 2: Comparison of platooning with ride-sharing and freight consolidation

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

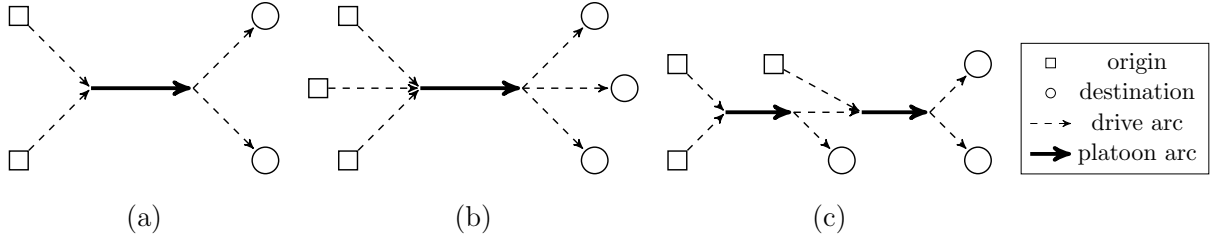


Figure 3: Examples of restricted platoon settings - (a) a two truck platoon - single platoon per trip, (b) a three truck platoon - single platoon per trip, and (c) a two truck platoon - multiple platoons per trip

4. Scheduled platoon planning

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

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

Restricted vs. unrestricted platooning As we discussed in section 2.3, there are likely to be restrictions on the number of trucks in a platoon in practice to restrict the impact on traffic and lessen the additional wear and tear on infrastructure. Furthermore, one may also want to minimize the number of platoons each truck is part of in a single trip to, for example, make the division of benefits simpler. Some examples of such restrictions are shown in figure 3.

Table 3 presents the platooning literature classified in this manner. We begin with a description of the unrestricted cases; then we introduce the different restrictions.

4.1. Unrestricted platooning

In the unrestricted setting, a truck may join and leave a platoon en route at any point in time. Moreover, there are no restrictions on the number of trucks in a platoon. A simple example of such a scenario with four trucks is depicted in figure 4.

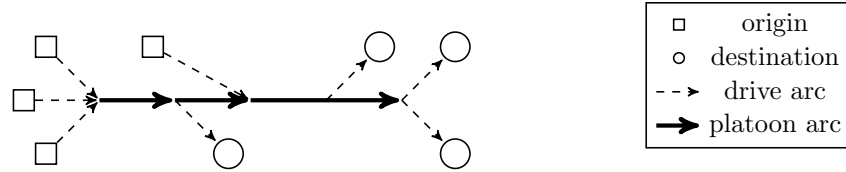


Figure 4: Unrestricted platooning - trucks allowed to join and leave a platoon at any instant

4.1.1. Unrestricted platooning - fixed routes

315 The conceptual problem for this setting involves determining the departure times and/or speeds of different trucks as to maximize the overlap in their routes which would correspond to a platoon. As driving in a platoon reduces fuel consumption, this objective would maximize the fuel savings from platooning.

Van de Hoef (2016) considers this problem for a large fleet of trucks. Using truck infor-
 320 mation, a centralized coordinator computes the vehicle plans for each truck which contain the routes and speed profiles so that they reach their destinations before the deadlines. The problem is to find the set of vehicle plans that minimizes the total fuel consumption. To do so, a list of feasible platoon pairs is found taking into consideration the overlap in the routes and the time schedules. For each platoon pair, the optimal speed profiles are computed us-
 325 ing a fuel consumption model. These platoon pairs are then merged together into one plan that contains the vehicle plans of all the trucks. The associated combinatorial optimization problem is shown to be NP hard and a local improvement heuristic for the fuel savings is presented to solve large problem instances. Then, the timings of platoon formation and split up are adjusted in a convex optimization problem to minimize fuel consumption. They test
 330 their approach with random transport assignments in mainland Sweden with up to 2000 trucks. They observe that the local improvement heuristic produces savings within thirty percent of the upper bound.

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

down in addition to the following vehicle speeding up to form platoons and conclude that it
340 is more efficient.

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

350 As we explained earlier in section 2.2, having too many trucks on the same road to
maximize the platooning potential could cause congestion and be detrimental to the system.
This will occur if the number of trucks exceeds the capacity of a link. The area of traffic flow
research could be used to look into this aspect. Traffic assignment models aim to minimize
travel time in the system by assigning vehicles to specific links in the network. For examples,
355 see Angelelli et al. (2016), Merchant and Nemhauser (1978). Using this line of reasoning,
Farokhi and Johansson (2013, 2014) consider vehicles that decide their time of travel based
on their preferred time, average traffic velocity and the congestion tax at that time. Trucks
that can platoon have an additional incentive use the road at the same time as other trucks.
They model the problem as a congestion game and use game theoretic concepts to study
360 how the traffic flow and platooning incentives interact. One of their observations is that if
there are more fuel savings associated with platooning, more trucks start travelling in similar
time intervals. In this study, the authors consider a single stretch of road and therefore, the
routing element isn't involved.

4.1.2. Unrestricted platooning - flexible routes

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

problem.

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

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

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

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

The area of convoy planning provides some parallels to this platoon setting. This is primarily used in military applications where safety and therefore, time are crucial consider-
410 ations. The study by Valdés et al. (2011) can be seen as a special case where a transportation unit in a city needs to merge with a convoy that is travelling in a circular path across the city. They use dynamic programming to route the transportation unit to the convoy in an efficient way. The synchronized arc routing problem (Salazar-Aguilar et al., 2011) also shares some characteristics with the platoon planning problem. This problem also involves
415 synchronizing the routes of multiple vehicles. Salazar-Aguilar et al. (2011) propose a local search heuristic to solve this NP-hard problem for large instances.

4.2. *Restricted platooning*

Section 4.1 presents several studies that address different variants of the unrestricted platoon planning problem. It is, however, not clear if the solution approaches developed for
420 these unrestricted settings would also be effective in the more restricted settings. Certain restrictions may be exploited by making use of specialized algorithms. For instance, Agatz et al. (2011) are able to solve large instances of the ride-sharing problem to optimality by restricting the number of riders per ride-share match. Nevertheless, the introduction of restrictions may also complicate matters as it makes it more difficult to find feasible solutions.

425 4.2.1. *Restricted platooning - fixed routes*

This setting also represents a scheduling problem where we need to determine the departure times/speeds of trucks given predetermined routes. Here, restrictions such as the ones relating to the platoon size or number of platoons per trip (see figure 3) need to be taken into account.

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

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

If we aim to reduce the inconvenience or waiting times for the trucks to form platoons,
450 this setting resembles the area of schedule synchronization in public transit (see Wong et al. (2008); Daduna and Voß (1995); Voß (1990); Domschke (1989) for examples).

4.2.2. Restricted platooning - flexible routes

In this setting, we need to determine the routes of the trucks in addition to the schedules/speeds of the trucks while taking different restrictions into account. While this platoon

455 setting is the most general and realistic, we are not aware of any study that explicitly studies
this setting. However, there are similarities with other well-known problems especially when
we consider platoons of at most two trucks. Two-truck platoons are likely to be prevalent
particularly in the initial stages of deployment.

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

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

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

Ride-sharing is a special case of the well-known general pick up and delivery problem.

485 The general pick up and delivery problem (Savelsbergh and Sol, 1995) considers vehicles
that need to fulfil transportation requests by picking up goods at their origins and delivering
them to their destinations. This can be extended to truck platooning where instead of goods,
trucks need to be “picked up”. Unlike the traditional pick-up and delivery problem, there
are no fixed start and end locations defined as both vehicles are mobile. This is linked to
490 the vehicle routing problem with roaming delivery locations. This problem considers the
deliveries of shipments to the trunk of a customer’s car (Reyes et al., 2016).

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

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

505 Table 4 provides an overview of the methods and instances considered by the various
studies.

5. Levels of human involvement in platooning

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

Table 3: Classification of platooning literature

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

* special case/ sub-problem

platooning.

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

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

520 5.1. Human driven platooning with in-platoon resting

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

525 Legal stipulations also control the amount of time for which a driver is allowed to drive. That is, truck drivers in most countries are subject to limits on their driving times before being required to take a break. The regulations depend on the type of vehicle and the country. For example, EU regulations state that a driver must take breaks totalling at least 45 minutes after a maximum of 4.5 hours of driving (Government-UK, 2016). Similarly, in
530 the US, a break of 30 minutes is required after at most eight hours after a driver begins his duty (Goel, 2014). Regulations typically also prescribe weekly limits in addition to the limitations within a day. See Goel (2014); Goel et al. (2012); Goel and Rousseau (2012);

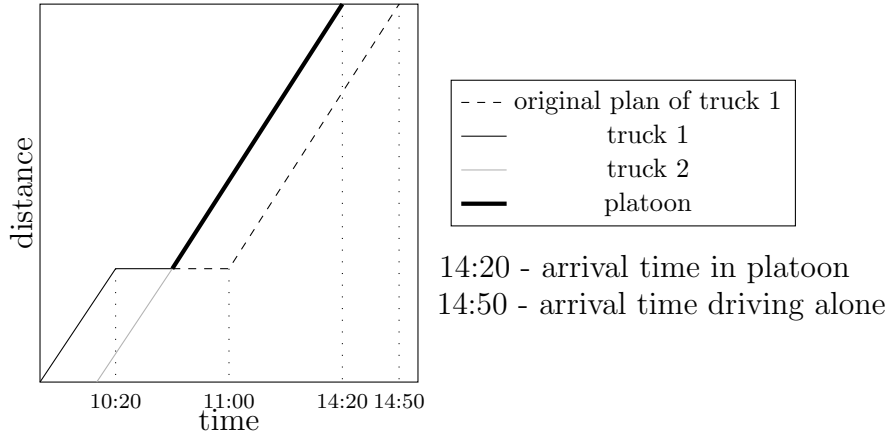


Figure 5: Increased productivity when the driver of truck 1 can take a break in a platoon

Goel (2010) for a detailed overview of different regulations. In this setting, the time as the follower in the platoon would not count as formal driving time.

535 Allowing breaks during a platoon will relax break-time constraints and as such improve the overall transport efficiency. In particular, it may help increase the productivity of the drivers as they can cover more distance in the same time. Figure 5 illustrates the benefits of being able to take a break within the platoon. The example considers two trucks that share a portion of their route. Truck 1 starts a 40 minute break at 10:00. Ten minutes into his
 540 break, truck 2 arrives at the location. Instead of waiting to finish his break, the driver of truck 1 can now finish the last 30 minutes of his break as a following truck of the platoon. This implies that truck 1 now arrives at its destination at 14:20 instead of 14:50. Therefore, there is an improvement in the transit time and associated costs.

The example described in figure 5 considers a two truck platoon where each truck is
 545 part of only one platoon in its trip. The same idea can fairly easily be extended when we consider platoons of more than two trucks. Just like the example, the change will affect only the trucks in that platoon. It is, however, more complicated when a truck may be part of multiple platoons per trip. Since the different platoons in a trip are interdependent, any change made to the break of one truck will affect all the platoons in the trip of that truck
 550 and, in turn, all the platoons in the trips of the trucks part of the said affected platoons and so on. Therefore, the problem’s computational complexity grows rapidly.

At the same time, there is an additional layer of complexity that needs to be considered

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

5.2. Hybrid platooning

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

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

Hybrid platooning also gives rise to new opportunities with regards to driver roles. The drivers may have different duties such as a platoon leader or a last mile driver. Furthermore, during the pick up and delivery of drivers, drivers may swap roles. The driver dropped off

may take over as the leading driver of the platoon while original platoon leading driver may take over the decoupled truck and complete its final leg. This is specially relevant for the planning of shifts and breaks. This is linked to the general area of crew scheduling (see Ernst et al. (2004); Raff (1983)). Vehicle routing and crew scheduling has been done in parallel in most of the literature (see Hollis et al. (2006) for an overview). Drexl (2011) mentions that the truck and trailer approach could also be used in this way. The drivers may be considered vehicles which can couple with a truck that is left at intermediate locations.

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

5.3. *Driverless platooning*

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

6. Real-time platoon planning

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

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

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

Based on historical information, we may have some probabilistic information about future events. For instance, historical data could provide an indication about trip announcements
630 from freight transporters. For instance, if it is known that some trucks traverse the same route fairly regularly, there is a high probability of them being able to form platoons.

Adler et al. (2016) look at a case of real-time platooning of multi truck platoons from a queueing perspective by considering historical data to model the arrival of trucks. They consider a Poisson-distributed series of vehicles arriving at a particular station and all headed
635 towards a common destination. The vehicles form platoons at this station and drive together as a single platoon to the common destination. Therefore, they allow the formation of multi truck platoons. Vehicles can wait for each other at the station but this will increase the delay. They look at this trade-off between energy savings and delay. Two sets of platoon formation policies are defined - all the trucks at the station leave as a platoon when either

640 a certain time period has elapsed or a threshold platoon size is reached. On comparing these two sets of policies, they observe that the performance is dependent on the size of the platoons produced. The threshold platoon size policies allow an average of one truck more per platoon than the time table policies. As a consequence, the threshold policies perform better in terms of the energy saved for a given delay.

645 Moreover, the stochasticity of information links the problem to the area of stochastic vehicle routing (Gendreau et al., 1996). See for example, Bent and van Hentenryck (2004); Powell (1996) for the usage of stochastic information in dynamic settings. Furthermore, the travel times of trucks could be uncertain due to the weather, traffic amongst other factors (van Lint et al., 2008). For examples with stochastic travel times, see Kenyon and Morton
650 (2003); Laporte et al. (1992). This was considered by Zhang et al. (2017) as described in Section 4.2.1.

7. Vehicle routing with platooning

Instead of planning only single trips from an origin to a destination, one could also consider platooning opportunities for routes with multiple stops. If there is flexibility in the
655 sequence of stops, there is more room to form platoons.

Figure 6 shows an example in which the number of platooning opportunities may be increased by changing the sequence of stops. The figure shows the routes of two trucks with their stop sequences. Initially, there is no common path in their routes and, therefore, no opportunities to platoon. Switching the order of stops c and d on route 1 gives rise to a
660 platooning opportunity between stops b and d .

This combines platoon planning with vehicle routing. There is a large body of research on solution approaches for the vehicle routing problem. Laporte (1992) provides an overview of these different approaches. In the usual variant of the problem, the loads need to be assigned to vehicles subject to the capacity constraints. The trucks could operate out of a
665 single depot or multiple depots (for examples of the multi depot setting, see Crevier et al. (2007); Lim and Wang (2005); Cordeau et al. (1997); Renaud et al. (1996)).

When all trucks belong to the same fleet or company, the problem can be solved by considering a vehicle routing problem that incorporates platooning opportunities. This is

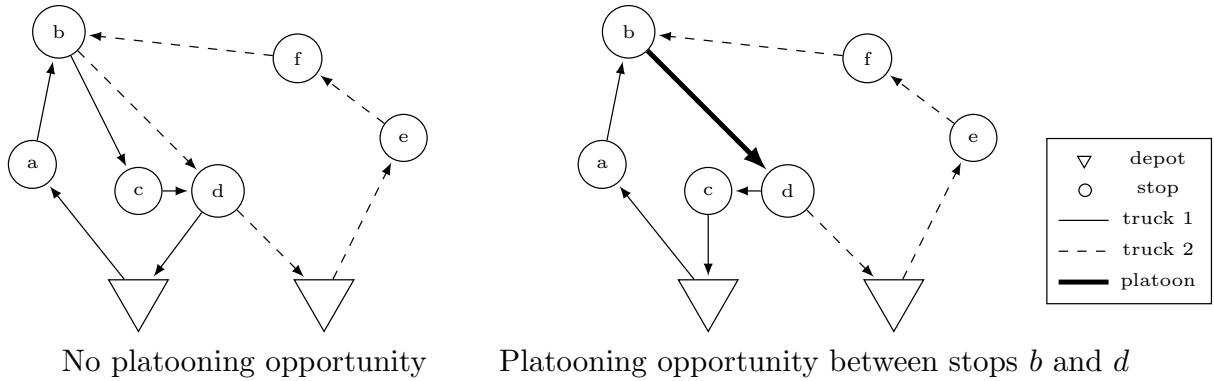


Figure 6: Changing the sequence of stops to create a platooning opportunity

different from the standard vehicle routing problem since the routing overlap creates platooning opportunities. Instead of just the shortest path, we need to consider multiple paths
670 between a pair of points to maximize the platooning opportunities.

When multiple fleets are involved, there may be practical restrictions on the assignments of vehicles to stops. That is, the stops allocated to each fleet are known in advance and we have fixed clusters. This means that the route assignments are fixed and there is flexibility
675 in the sequence of stops. This links the problem to the area of cluster first, route second vehicle routing literature (see Prins et al. (2014) for an overview). Here, the customers are clustered together and the customers in a cluster are visited by the same truck. The routing phase can be treated as solving a travelling salesman problem with time windows within each cluster (Laporte et al., 2000).

680 8. Network design and platooning

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

The strategic level decisions involve long term aspects such as physical network design
685 (Crainic, 2000). For instance, parts of the network may be heavily used by platoons and require infrastructural changes such as reinforcement of roads, new lanes, additional communication support in tunnels etc. A similar rationale is used in the context of automated vehicles by Chen et al. (2017, 2016). Also, since the starting locations of trucks influence

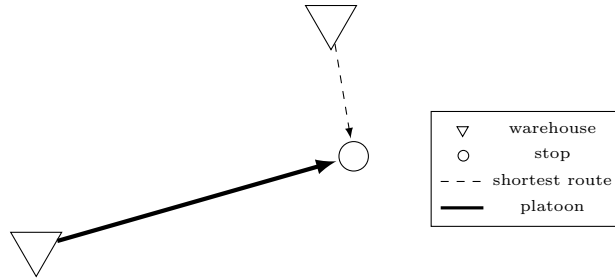


Figure 7: Change in order assignments because of platooning

platooning opportunities, there is an incentive to move facilities such as warehouses and
 690 depots closer to each other. This relates to the concept of economies of agglomeration (see
 Glaeser (2007)).

Tactical level decisions relate to service network design which involves decisions mainly
 pertaining to the organization of services, and the routing of freight. Crainic (2000) provides
 an overview of research in this area. Because of increased platooning opportunities, certain
 695 orders may be assigned to different warehouses than the ones closest to the shipment location.
 Figure 7 shows a simple example of such a situation. The flexibility of platooning means that
 this decision should be made as late as possible based on real-time platooning opportunities
 on the different routes. Xu et al. (2009) look at a similar problem in the e-commerce setting
 citing the dynamic nature of the system. This dynamic nature also creates a link with the
 700 dynamic service network design problem (see Dall’Orto et al. (2006)). Additionally, we can
 view the flexible formation of a platoon as an instantaneous switch in the transportation
 mode. This links platooning to the multimodal network design problem (for an example, see
 Yamada et al. (2009)).

9. Conclusions and future research

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

This paper outlined various planning challenges encountered in platoon planning. Also,
 710 the paper provided an overview of relevant operations research models from different areas.

Table 4: Overview of platoon planning literature

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

*use an arrival rate of trucks

Table 4 provides an overview of the platoon planning literature discussed in this paper. From tables 1, 3, and 4, we see that there are several papers that address various problems but approaches to deal with the dynamic, advanced, and restricted forms of platooning etc. are still lacking. More specifically, the areas for future research include -

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

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

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

Dealing with uncertainty. Areas relating to real time planning are of interest. In practice, the information continuously changes with trucks entering and leaving the system.
730 Also, travel time uncertainty represents a realistic scenario but is more complex to solve

and implement. Zhang et al. (2017) do study stochastic travel times but in a small setting. Moreover, we are not aware of any research dealing with stochastic and dynamic arrivals of trucks for platooning.

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

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

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

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

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

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

Incentives could again play a role here. Given the societal benefits of platooning, the
760 government may want to encourage some of the (expected) effects so that forming platoons

becomes easier. Additional research into the effects of platooning on the network will help this cause.

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

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