



Truck Platooning Business Case Analysis

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Abstract

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In this report we describe results from the work on business case analysis of the Sweden for Platooning (S4P) project. Platooning has the potential to contribute to the on-going transformation of the transport sector by reducing environmental impact, saving fuel, as well as (to a lesser extent) by improving traffic flow and safety and in the long run reducing driver hours. In order to fulfil these promises, it must be shown that there are viable business cases for all involved actors. This report describes the analysis of truck platooning business cases performed in the S4P project.

Some of the main findings are that there is a significant potential for reducing fuel consumption and hence CO₂ exhaust through platooning; that waiting on the order of minutes for a platooning opportunity is reasonable but that taking another route is probably not; that it is necessary to have *mediating services* that help platoons to form and share the costs and benefits associated with platooning; and that there are different possible ways of implementing a system for sharing the benefits.

Keywords: Platooning, Business case analysis, System of systems

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Cover picture: Trucks from Scania and Volvo.

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1 Introduction

The transportation sector is continuously trying to improve its energy usage, in order to reduce its environmental impact and save fuel costs. This has traditionally been achieved by optimizing individual vehicles and their propulsion. However, the potential for further improvements of the vehicles is gradually shrinking, and other approaches must be sought.

One possibility is to improve how vehicles are used, and how they interact with others in the traffic environment. This has led to considerable research into truck platooning (see for instance (Switkes, Boyd, & Stanek, 2014); (Souza Mendes, Fleury, Ackermann, & Fabrizio, 2017); and (van Vliet, Jansen, & Cornelissen, 2015)). The idea of platooning is that a manually driven lead vehicle is followed closely by a number of other vehicles using automated driving (either only longitudinal control, or both longitudinal and lateral control). The benefit is that aerodynamic drag can be substantially reduced by shortening the distance between the trucks, leading to lower fuel consumption. However, there are also costs related to this, including the fact that trucks may have to wait for each other in order to be able to form a platoon, with negative effects on transport efficiency. A complicating factor is that the first vehicle in the platoon (the leader) gets a smaller reduction in fuel consumption than the others, and there might be a need to compensate for this imbalance through business transactions.

In addition to reducing the environmental impact from transport, platooning also has the potential to improve traffic flow and safety, both for platooning participants and the surrounding traffic. Platooning also has the potential to help mitigate the lack of truck drivers. The purpose of this report is to analyze the overall business case of truck platooning from various perspectives.

1.1 Project overview

Communication between trucks is necessary both to be able to form platoons and to coordinate the driving within a platoon. To reach the full potential of truck platooning, trucks from different brands must be able to communicate and find each other.

The Sweden for platooning (S4P) project, funded by Vinnova – Sweden’s Innovation Agency under the Strategic Vehicle Research and Innovation (FFI) programme (grant no. 2016-04232 and 2016-04233), demonstrated the feasibility of multi-brand platooning by showing that trucks from Volvo and Scania are able to platoon together. The project ran from 2017 to 2019 and in addition to Volvo and Scania included participation from KTH, RISE SICS, Schenker, and the Swedish Transport Administration (Trafikverket). The project included work packages on use case specification and safety analysis; on-board functionality; off-board functionality; pilot and evaluation; demonstration; and business models.

This report presents the main findings of S4P in the area of business models. An overview of the S4P project is given in (Dellrud et al, 2020).

1.2 Research questions

The work on business case analysis started with an initial brainstorming of research questions. The research questions were collected into a hierarchical structure and then investigated by different means. In some cases, interviews with stakeholders were performed, while in others simulation studies or analytical investigations were done.

The highest-level research questions selected at the start of the project were:

- *Corporate costs and benefit.* What are the costs and benefits of platooning? How big are the fuel reductions? What is the cost of waiting to form a platoon? What is the cost of re-ordering a platoon?
- *Payments.* Is there a need for payments between trucks to share the benefits and costs of platooning? If so, how should the payments be organized?
- *Coordination.* How should a platoon be coordinated? How should they form, operate, and dissolve? In what order should the vehicles in a platoon drive? Should the vehicles re-arrange themselves in order to spread the fuel reduction benefit more equally? This report deals with the business aspects of these issues, while the technical aspects are addressed elsewhere.
- *Societal perspective.* What are the consequences and potential for the society and other road users and how can their acceptance of platooning be assured?

1.3 Report overview

In this report, we give an overview of the work done to answer these questions. First in Chapter 2 we present traffic scenarios and other assumptions for platooning in Sweden and discuss design issues for platooning. The traffic scenarios are based on the data analysis given in the Appendix. The potential societal benefits (including effects on safety and the possible need for different technological levels of platooning to coexist) of platooning in Sweden are then described in Chapter 3. Chapter 4 deals with modelling the costs and benefits of platooning, and provides quantitative estimates of, *e.g.*, fuel savings and cost of waiting times as well as the cost of reordering the vehicles in a platoon. Chapter 5 presents work on how to form platoons while the role of mediating services for ensuring that platoons can form and that costs and benefits are distributed in a fair way is the focus of Chapter 6. Finally, some conclusions as well as suggestions for future work are given in Chapter 7.

The report is the result of joint work by all authors, but with one or two authors responsible for each chapter, as follows: Chapter 2 (Torsten Bergh, Björn Mårdberg), Chapter 3 (Torsten Bergh, Björn Mårdberg), Chapter 4 (Björn Mårdberg, Viktor Åkesson), Chapter 5 (Jakob Axelsson, Alexander Johansson, Pontus Svenson), Chapter 6 (Jakob Axelsson). The Appendix was written by Torsten Bergh. Pontus Svenson was the main editor of the joint report.

In addition to the authors, several other persons contributed to the work on business models in the project, in particular Jan Dellrud (Scania), Hamid Zarghampour (Trafikverket), Sebastien van de Hoef (KTH).

1.4 Glossary

In this section we provide definitions of some acronyms and technical terms used throughout the report.

Term	Explanation
Articulated truck	A truck combination with a pivot joint, i.e., a rigid truck and trailer; a tractor and semitrailer; or a rigid truck, dolly and semitrailer.
Dolly	A dolly is an unpowered trailer which can be attached to trucks, tractors and road trains. The dollies themselves don't carry a load but are used to support a semi-trailer or similar haulage unit.
Eurocombination	A tractor-semitrailer combination, at most 16.5 m long.
Gap	The distance between two trucks from the tail of the first truck to the head of the second. Can be measured as distance or converted into time.
Heavy truck	Truck weighing more than 3500 kg.
Headway	The distance between two trucks from head to head.
Nordic combination	A truck-trailer combination, at most 25.25 m long, typically a rigid truck pulling a dolly and a semitrailer of total 24 m.
Rigid truck	A truck with cargo space on the truck itself, can be used separately (typically for distribution) or in combination with trailer (typically for long haul).
Semitrailer	A trailer with only rear wheel axles, the front of the trailer is attached to a tractor or a dolly.
System of systems (SoS)	A collaboration between independently owned and operated constituent systems in order to achieve benefits that the individual systems cannot achieve on their own.
Tractor	A truck (without cargo space) made for pulling a semitrailer.

2 Assumptions and traffic scenarios for platooning

Main authors of this chapter: Torsten Bergh and Björn Mårdberg

In this chapter, we will discuss important platoon design issues, probable market penetration and present fuel and time consumption for society. We start by listing some important design issues for platooning, followed by a description of the traffic scenarios considered in S4P. The detailed traffic data presented in the Appendix is then used to estimate market penetration and fuel and CO₂ exhaust.

The statistics presented here are used in the next chapter to determine the potential societal benefits of platooning.

2.1 Design issues for platooning

Within the S4P project, platooning will only be considered on motorways. It is reasonable to assume that platooning will first be used/allowed on motorways during off peak hours where traffic flows are not close to maximum capacity. This would avoid challenges such as a major need of lane changes, overtaking using the lane for opposing traffic and conflicts with vulnerable road users. These are traffic situations requiring more sophisticated platooning technology and with clearly higher safety challenges. A second stage for platooning in Sweden is probably 2+1 median guard-rail roads. It is also reasonable to assume platooning to be more interesting and more easy to deal with for long distance/time truck traffic, *i.e.* truck combinations.

There are several design issues that have an impact on the costs and benefits of platooning:

- Trucks are never allowed to break the speed limit. Keeping the speed limit is the legal responsibility of the drivers. We assume that all vehicles in platoons stay within speed limits when assessing the effects of platooning. While the focus of the S4P project is on platooning with drivers in all vehicles, a possible future introduction of fully automated follower vehicles could enforce this in software.
- How slowly should trucks be permitted to drive compared with their regular speed and the speed limit to wait for and join a platoon?
- What are the driver rules when changing position or leaving the platoon? Should normal traffic rules apply for lane changes?
- For how long are trucks allowed to overtake and thus block the motorway? The main motorway problem today is probably trucks overtaking with marginal speed differences. This problem would be reduced if platoon members adapted their speed for reorderings.
- How to deal with cut-ins, *i.e.*, an intruder breaking into the platoon?
- How should or should not other drivers be informed that they are coming closer to or are overtaking a platoon?

- Should a “platoon sign” be used similar to the “long vehicle sign” and other supplementary measures due to the “over lengths”?
- What rules should apply when travelling through an interchange area? Is platooning allowed and if so how long is the platoon allowed to be?

The following assumptions have been made in the assessments to come:

The decisive factors for the overall benefits of platooning are annual mileages and weights; present speed and platooning behaviour; assumptions on possible share of platooning in relation to overall traffic volume; average platooning vehicle number; platooning gaps (tail to front between successive vehicles); and platooning fuel savings due to speed, gap and position.

When quantifying the costs and benefits of platooning, there is a need to convert time and fuel into money. The conversion factors used for this are different for the societal and business perspective.

2.2 Traffic scenarios

To determine what traffic scenario to analyze, we looked at where we believe that platooning will be first used in Sweden. Platooning may very well be feasible in other traffic scenarios too. The assumptions underlying the analysis done are listed in this section.

Platooning will mainly be applied on long distance transports here defined as truck combinations.

The first market segment will be rural motorways, *i.e.*, with speed limits 110 and 120 km/h at good road surface and sight conditions and outside interchange areas. Platooning could technically be active also at interchanges but larger gaps should then be used.

80 km/h is assumed as the legal speed for trucks with trailers, and overspeeding is not accepted. Trucks without trailers are allowed to travel at 90 km/h. The main interest in this project is long-haul, which usually entails a tractor-semitrailer or a truck-trailer combination.

When analyzing effects on other traffic due to one or more trucks slowing down for coordination reasons, in some examples a lower truck speed limit of 70 km/h will be assumed.

Forced lane changes are not accepted. Platoon position overtakings are only allowed in off peak hours in more or less free flow conditions.

Platoons and slow movers are properly signed to inform and warn other drivers.

The normal time gap in platooning for analysis is assumed to be 1.0 s. By time gap we mean the time distance between two trucks measured from the tail of the first truck to the front of the second.

Main assumed traffic intensity: 2000 vehicles/h in one direction = 1000 vehicles/h per lane¹. These numbers are for motorways with 2 + 2 lanes.

The analysis is done for Sweden.

2.3 Traffic flows, truck combination shares and weights

In order to analyze the overall platooning potential, it is necessary to have data on traffic flows and truck combination shares in the relevant situations. What are the truck combination flows on these 110 and 120 km/h motorways? What do we know about their gross weights? The following sources are available: Swedish Transport Administration (STA) traffic count (TRAFKA) and weight-in-motion (WIM) measurements and estimates from Handbook Emission Factors for Road Transport (HBEFA, 2019); and a report from WSP on traffic volumes in Sweden (WSP, 2015).

In this section, we present conclusions reached from analysing this data for motorways limited to 110 and 120 km/h, while a detailed overview of available data can be found in Appendix A.1 and A.2.

The results of the data analysis are:

- Articulated truck mileage: $0.085 \times 12.8 = 1.1$ billion km (2018). This corresponds to about 30% of total mileage.
- Rigid truck mileage: more uncertain, but in the range $0.024\text{-}0.07 \times 12.8 = 0.3$ to 0.8 billion km.
- WIM average gross weights (2018) were 12 for rigid trucks, 19 for buses (with an over all rigid average 13), 30 for semi trailers and 41 tons for truck and trailers. HBEFA reports 18 for rigid trucks and 35 as an average for semis and truck and trailers. The latter coincide well but there is a large discrepancy for rigid trucks.

There is thus a large traffic volume where platooning could potentially be of benefit. Including also 2+1 median barrier roads would add an additional 7.8 billion km mileage.

2.4 Traffic volume and speed in current traffic

Considering the data in Appendix A.3, we see that traffic volumes in peak hours are as medians around 1 300 vehicles/hour with a few extremes up to the double and average flows 50% of the medians. These indicate average speeds to around 85 km/h for trucks with trailers (including semis), *i.e.*, over the legal speed limit 80 km/h.

For rigid heavy trucks and buses, the average speed is slightly below 95 km/h. Taking account of the facts that the measurement system cannot distinguish between buses and

¹ In reality, the vehicles are not equally distributed over the two lanes. For the analysis done in this report, the difference does not matter.

rigid trucks and that buses correspond to about 15% of traffic, this is reduced to about 94 km/h².

This is also valid for average peaks. There are however exceptions, particularly at a number of long up hills such as Jönköping and Hallandsåsen.

2.5 Fuel consumption and CO₂ exhausts

From the data shown in Appendices A.2, A.3, and A.4, we see that average 110 and 120 km/h motorway truck combination fuel consumption varies between over 4 liters/10 km according to the old EVA-model from 2008 and a VTI update proposal down to 3 liters according to an internal HBEFA-based Swedish Transport Administration model. Sveriges Åkeriföretag gives examples between 3 and 4.8 liters due to gross weight, driving conditions and driving style. Assumptions on gross weight, alignment and other issues are unclear in the model descriptions found especially for HBEFA results. Rigid truck fuel consumption varies less between the different sources lying around 2.3 liters/10 km at around 90 km/h.

The marginal fuel consumption for truck combinations in the speed interval 80 to 86 km/h valid for Swedish 110 and 120 km/h motorways is 20 to 35 ml per km/h and km for the new internal Swedish model (0.7-1.1 % per km/h) compared with 35 to 40 ml per km/h and km in the present EVA/VETO-model (some 0.9 % per km/h).

The marginal fuel consumption for rigid trucks in the speed interval 90 to 93 km/h valid for Swedish 110 and 120 km/h motorways is 20 to 29 ml (0.9 to 1.2 %) per km/h and km for the new internal Swedish model compared with around 30 (some 1.3 %) in the present EVA/VETO-model.

CO₂ exhaust is directly dependent on fuel consumption and the ratio of renewable diesel used. The conversion factor in the new model is 1.91 kg CO₂ per liter diesel, whereas in the old EVA/VETO model the factor 2.46 kg was used. The difference is due to different assumptions on ratio of renewable fuel used.

² The measurement system is based on axle distances, and hence cannot discriminate between buses and rigid trucks. Heavy trucks weighing more than 7.5 tons are required by law to have speed regulators, so cannot drive faster than the speed limit. The share of heavy rigid trucks under 7.5 ton is somewhere around 30% to 40%.

3 Potential of platooning

Main authors of this chapter: Torsten Bergh and Björn Mårdberg

In this chapter, we will discuss the effects of platooning on society and other road users. The background statistics referred to in the previous chapter are used to discuss the potential savings in fuel, CO₂ exhausts, and driver time that can be achieved by platooning. The effects of platooning on other vehicles on the road is then described, focusing on the safety aspects. The chapter concludes with some remarks on the possible coexistence of platooning on different technical levels.

The main corporate advantage in the short run is as already stated decreased fuel consumption due to improved air resistance, which also brings the societal benefits of reduced CO₂ and other exhausts. In the long run, a more important gain will be decreased driver costs if follower trucks can be autonomous or drivers can be allowed to conduct other tasks when in platoon. The socioeconomic costs for drivers per running hour is 267 SEK/h; for diesel around 400 SEK/h; financially up to 450 SEK/h; and for CO₂ from 50 to 350 SEK/h (Trafikverket, 2018). Secondary effects are impact on the commodity transport market and on level of service and traffic safety for other vehicles. Negative market share effects from an environmental viewpoint could be treated using taxation measures.

These effects depend substantially on in what traffic environments platooning is applied and also on how platooning is designed in traffic engineering terms. These two questions must be answered for any potential and effect assessment to be possible.

When discussing the platooning potential in this chapter, it is assumed that all opportunities for platooning will be used, i.e., that trucks will always platoon under assumed conditions. In reality, it is difficult to realize the full potential, and this is discussed further in Chapter 5 dealing with platoon formation.

3.1 Fuel and CO₂ saving potential

As stated in Section 2.1, we assume that the first market step is motorways in free flow to medium traffic flows with 110 and 120 km/h speed limit. The total truck mileage is somewhere around 1.1 billion (1.1 x 10⁹) kilometres annually (2018) for truck combinations and, more uncertain, 0.3 to 0.8 billion for rigid trucks.

Free flow conditions dominate, with average measured speeds around 86 km/h for articulated trucks and 93 km/h for buses or rigid trucks (see discussion in Section 2.4) at speed limits 80 km/h for articulated trucks, 90 km/h for rigid trucks, and 100 km/h for buses. Fuel savings will be made partly due to speed reductions down to the speed limit and partly due to platooning. Note that reduced speed will increase other costs (more trucks and drivers needed) – this is taken into account of in the calculations presented in this chapter.

If the average speed were reduced to 79 km/h, the average fuel savings is estimated as 24 million litres (according to the old EVA/VETO model) or 20 million litres (according to the new Transport Administration model). z

The platooning effect depends on platooning length and speed. Table 1 lists the assumption for fuel saving depending on gap and truck position used in the societal analysis. An average platooning gap of 1 sec with an average length of 3 trucks gives an average of 6% fuel reduction. The total effect depends on the average consumption and is in the same range as the speed limit effect with some 26 million liters according to the old models and 21 million liters according to the new ones. The rigid truck effect, should platooning be as effective, would be some 3 to 11 million liters.

Table 1 Fuel saving percentage due to platoon position and gap at 80 km/h according to this project.

Time gap sec	Fuel saving %	
	leader	follower
0.8	2	8.6
1	1.8	8
1.2	1.6	7.4
3	0.0	2.1

The total truck combination fuel consumption on motorways with 110 and 120 km/h is 2018 some 450 (old model) to 350 (new model) million liter diesel. Saving potentials are estimated to be around 25 million liters (using the old model) and 21 million liters (using the new model) for each of speed limit keeping and platooning. This is together some 12% of the present fuel consumption on these road types. The total cost (2020 diesel 6.2 SEK without taxes and 12.2 excl. VAT per liter) is 250 to 300 million SEK without taxes and up to 600 million SEK excluding VAT.

The rigid truck potential is smaller, some 20% to 50% of the possibility for truck combinations, due to the uncertainty in mileage estimate.

A secondary effect of this saving potential might be a market advantage for truck transports increasing truck transports and also increasing the market share.

The second market step would probably be rural 2+1 median guard-rail roads having a 2018 mileage of some 7.8 billion vehicle kilometres. These road types have similar truck combination shares as motorways. Measured truck and trailer speeds are slightly lower, 84 compared with 86 km/h. A rough estimate of the potential using the old model is 5 million liters due to speed limit keeping and 15 million liters due to platooning.

CO₂ exhaust is directly dependent on fuel consumption and the ratio of renewable diesel used. The conversion factor is 1.91 kg CO₂ per liter diesel in the new model and EVA/VETO 2.46 kg CO₂ per liter diesel in the old model. The difference is due to different assumptions on the ratio of renewable fuel. A 2018 fuel saving in the range of 50 million liter diesel means a CO₂ exhaust decrease in the range of 100 million ton. The socioeconomic value of this CO₂ reduction is today around 100 million SEK. This value will be increased to some 700 million SEK later in 2020 by a ASEK proposal (Garberg, Bengtsson, & Martini, 2019). The total socioeconomic annual fuel and CO₂ reduction value should then be some 1 billion SEK, 70% of which comes from the reduction in CO₂ exhausts. This could be compared with the corporate gain for truck combinations of some 600 million SEK. It must be noted that 50% of this gain derives from platooning and 50% from the trucks keeping legal speeds. To realize the full potential, it is therefore

necessary that platooning also leads to lower speeds, for instance by including speed regulators for the leader.

3.2 Driver time savings

The total truck combination mileage (2018) is estimated to be some 1.1 billion kilometers on 110 and 120 km/h motorways with an average speed of 86 km/h. Platoons are assumed to have an average length of three vehicles with an average speed of 79 km/h. While the scope of S4P is limited to platooning with drivers in all vehicles, in the future case where drivers in following trucks are allowed to perform other tasks than driving when platooning, driver hours could be decreased by some 8 million hours. The platoon effect is 9 million less drive hours, but the lower legal speed creates a 1 million hour travel time increase. The socioeconomic hourly driver cost is 267 SEK/h (ASEK 2017) giving a economic potential for society of more than 2 billion SEK. This could be compared with the potential corporate gain in fuel costs, see above, estimated to some 300 million SEK (without taxes) to 600 million SEK (only without VAT) or the combined societal fuel and CO₂ exhaust reduction of up to 1 billion SEK/year.

3.3 Safety effects for other vehicles

To estimate the safety effect for other vehicles, we need to start from current safety statistics and see how they could be influenced by platooning. A collection of relevant data for estimating the safety effect is found in Appendix A.5.

The (police-reported) truck accident risk and the light injury risk are higher than for car accidents (without trucks involved) on motorways. Severe injury and fatal and severe injury risks are close to each other though slightly higher for non-truck accidents. Fatalities and injuries in truck accidents are mostly drivers and passengers in cars. The risk level is around 0.10 truck accidents and 0.0007-0.001 fatalities and severe injuries per million truck kilometer. Rear end accidents are by far the most common accident type for trucks. “Snowy/icy” and moisty conditions have some 20% each on E4 and 25% on E6. There were 26 multi truck accidents on E6 and only 12 on E4. The reason is probably the long up hills at Landskrona and between Helsingborg and Halmstad.

It is again here assumed that platooning is restricted to motorways with 110 and 120 km/h with good conditions. This means that platooning should not be active during heavy rains and for road surfaces with bad friction. Whether platooning be allowed at exit and entry lanes is an open question; here we assume it is not permitted.

Platooning design rules are essential. Safety would probably be improved if platoons and slow moving trucks have to carry warning signs in the same way as long and slow-moving vehicles must today. More research is needed in the area of platooning safety, as indicated by the scarce results of research surveys on the subject (Axelsson, 2016).

The effect on safety by platooning will vary depending on the traffic situation. Some cases where platooning will have a positive effect are:

- Since the trucks in a platoon move synchronized, there will be fewer independent entities moving on the road. This will reduce the incidence of overtaking and lane changes (the major safety problems), positive for safety.
- Truck/platoon breaking will be more organized and smoother, also positive for rear ends.
- Truck overtakings/platoons causing blockages and lane changes is a safety problem today, see data from E6. Truck overtakings are forbidden today on some sections. The resulting platooning effect depends on design, see above. There are possibilities to decrease this problem.

Traffic situation where platooning could have a negative impact on safety are:

- Platoon follower drivers could be less attentive than when driving independently, thus increasing risks, *e.g.* at road surfaces with less friction and others. This risk is difficult to assess.
- There are also various safety risks within a truck platoon driving at short gaps. The shorter the gap, the higher the risk.
- Slow moving trucks in order to join a platoon is a safety risk. This risk depends on how slow speeds are allowed and what rules are adapted for how slow-moving vehicles should be equipped with warning systems.

Two interesting platoon design issues are reordering within the platoon and generally maximum speed.

The decrease in truck to truck overtakings is probably the major safety benefit. Reordering within the platoon, however, entails overtakings. Rules for reordering that minimize the risks can, however, easily be designed.

Truck combinations are generally speeding today on motorways. Platooning with legal speeds should increase truck safety. This effect could be estimated using the speed/power law (Nilsson, 2004) with a power 4 effect on fatalities and 3 on severe injuries, giving fatality 30% ($1-(79/86)^4$) fatality and 20% severe injury risk decrease.

It is hard to predict the summarized safety effect. The general feeling is that there are possibilities for a positive effect.

3.4 Level-of-service effects for other vehicles

As in earlier parts of this report, it is assumed that platooning in a first step is restricted to motorways with 110 and 120 km/h with good conditions. If there is heavy rain or road surfaces with bad friction, the gap distance would need to be increased if platooning should be applied. It could also be discussed whether platooning should be allowed at exit and entry lanes. The restriction here is not to permit this.

The main level-of-service effect is platoon behaviour at platoon reorders/overtakings. Trucks overtaking each other with minor speed differences is probably the most important motorway level-of-service problem today together with truck speed

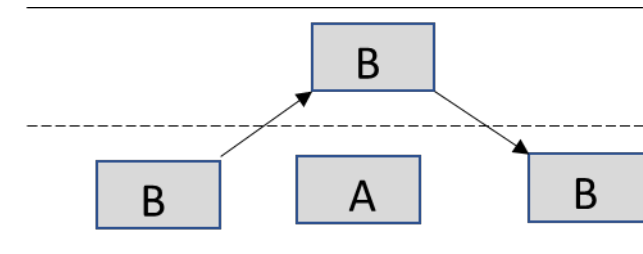


Figure 1 Truck overtaking.

performance on longer uphill sections such as Hallandsåsen on E6 and E4/Rv40 at Jönköping.

Figure 1 shows a truck B that overtakes another truck A. If they are both 25 m long with a speed difference of 1 km/hour, two motorway lanes will be blocked for almost 2 minutes for other faster vehicles. This might create “road blockage” and shock waves with stop and go traffic as a result. Overtaking prohibitions have been implemented on a number of motorway sections to ease this problem. It would thus probably be beneficial that the platoon leader reduces speed to facilitate the reordering; as for the safety issue mentioned below, simulation are needed to quantify this effect.

There are no Swedish empirical statistics available on these overtakings and problems caused.

The situation is also a safety problem as described in the previous section. Platooning will positively decrease the number of truck platoons and due to design also the number of truck overtakings at low speed differences. This would be a very positive effect. It would be possible, given a lot of assumptions, to simulate and quantify this effect. The assumptions, however, would be difficult to validate and results would more be examples/illustrations. The same partly contradicting factors are valid as in the safety analysis above.

Platooning before and along interchange exit and entry lanes might impact level-of-service in a negative way. Other drivers exiting might be unable to find a gap in the platoon to find their way to the exit lane creating overtaking lane disturbance. This is an obvious capacity problem already at higher flows but not a big deal at free flows. Drivers trying to enter the motorway might in the same way have problems and thus “collapsing” the entry. This is also a problem today in higher flows, and in fact platooning could reduce this if functionality to adapt intra-vehicle gaps according to traffic is developed.

3.5 The effect of different levels of platooning coexisting

We expect platooning to develop step by step, and hence assume that trucks whose equipment comes from different such “steps” will be on the same roads at the same time. So, how should these trucks handle each other when it comes to platooning?

3.5.1 Levels of platooning

Two trucks may be on different “levels” of platooning in several ways. One may be compliant to time gaps down to for instance 1.0s and another one may be able to handle time gaps down to for instance 0.5s. One truck may have a system with both longitudinal control and lateral control, whereas another truck requires the driver to handle the steering (lateral control) at all times.

So far there is no commonly accepted definition that specifies different levels of platooning. For the analysis here we will just assume that there are two levels, which we denote A and B, where B is the more advanced alternative. The benefit associated with level A is assumed to be $a = 1$, which is associated to each connection (or gap) between trucks who platoon on level A. So if two trucks, each on level A, platoon together, the total benefit will be $a = 1$, and depending on the existence of a profit sharing system (see Chapter 4) this benefit might be shared between them. In a similar way we also have the benefit b connected to platooning on level B, so if two trucks platoon on level B, the total benefit associated with their connection is b . We assume that $b > a$.

3.5.2 Backwards compatibility

If two trucks driving after each other are compliant to platooning levels A and B respectively, it is obvious that if the B truck is *backwards compatible* with the A truck, then they can perform level A platooning together, and the shared benefit attained will be a . If level B platooning is not backwards compatible with level A platooning, then this opportunity is lost.

Now consider three trucks in random order and with randomly selected platooning level A or B. Further assume level B platooning to be associated with benefit $b = 2$. Table 2 illustrates the loss of benefit if there is no backwards compatibility.

Table 2 Example of total benefits with or without backwards compatibility for three random trucks on platooning levels A and B when the benefits associated with each level of platooning are $a = 1$ and $b = 2$.

Levels	Benefits		Benefits		
	lead-middle-tail	w/o compatibility	with compatibility	w/o compatibility	with compatibility
AAA		$a + a$	$a + a$	2	2
AAB		a	$a + a$	1	2
ABA		0	$a + a$	0	2
ABB		b	$a + a$ or b	2	2
BAA		a	$a + a$	1	2
BAB		0	$a + a$	0	2
BBA		b	b or $a + a$	2	2
BBB		$b + b$	$b + b$	4	4
Average per truck:			0.50	0.75	
Relative to with compatibility			-33%	0%	

In this example the total gained utility of platooning will be 33% less if technology for level B platooning is not backwards compatible with level A. In Table 2 it was assumed 50/50 distribution between the two levels, and the benefit with level B was assumed twice that of level A, so $b/a = 2$. Table 3 lists the reduced benefit for some other distributions and Level B improvements.

Table 3 Loss of benefits due to lack of backwards compatibility for three random trucks for different distributions of platooning levels and different factors of improvement from one platooning level to another. Level B is the improved platooning level compared.

Loss of benefit w/o backwards compatibility		Distribution B/A				
		10/90	25/75	50/50	75/25	90/10
Improvement factor b/a	1.25	-18%	-36%	-45%	-31%	-14%
	1.5	-18%	-35%	-41%	-25%	-10%
	2	-17%	-32%	-33%	-16%	-6%
	3	-17%	-30%	-27%	-12%	-4%

The numbers in Table 3 indicate that the losses due to not having backwards compatibility are larger when the improvement is smaller. They also indicate that the losses are smaller if the two levels are unevenly distributed on existing trucks.

In the examples above it was assumed that the involved trucks were randomly ordered. Another possibility would be that they were arranged in a certain order by purpose. For instance instead of the BAB combination, one possibility would be that the first B truck lets the A truck pass, and then the two B trucks can form a platoon. For such cases, there would be less negative impact from not having backwards compatibility.

3.5.3 Mixed platoons

Mixed platooning means that the same platoon contains “links” or gaps that are associated with different levels of platooning. At least three trucks in the same platoon are needed for this concept to make sense.

For instance there could be a level A truck leading a platoon with three trucks, and the gap between the first and the middle truck could be 1.0 seconds, while the gap between middle and last truck could be 0.5 seconds if those two trucks were level B trucks. If mixed platooning is not possible, then either the three trucks could perform level A platooning, assuming the B trucks are backwards compatible with level A, or the B trucks could perform level B platooning on their own, not joining with the A truck in front of them.

Table 4 summarizes the possibilities and associated benefits for three random trucks, each on level A or B, depending on whether mixed platooning is an option or not.

Table 4 Example of total benefits with or without backwards compatibility for three random trucks on platooning levels A and B when the benefits associated with each level of platooning are $a = 1$ and $b = 2$. Backwards compatibility is assumed for both cases here.

Level	Gap distances		Benefits		
	lead-middle-tail	w/o mixed option	with mixed option	w/o mixed option	with mixed option
AAA		$a + a$	$a + a$	2	2
AAB		$a + a$	$a + a$	2	2
ABA		$a + a$	$a + a$	2	2
ABB		$a + a$	$a + b$	2	3
BAA		$a + a$	$a + a$	2	2
BAB		$a + a$	$a + a$	2	2
BBA		$a + a$	$b + a$	2	3
BBB		$b + b$	$b + b$	4	4
Average per truck:				0.75	0.83
Relative to without the mixed option:				0%	11%

The numbers in Table 4 are for a 50/50 distribution of B versus A trucks and for improvement factor $b/a = 2$. In Table 5 some examples for other distributions and improvement factors are given.

The numbers in Table 5 indicate that the benefits of allowing mixed platooning is reduced for smaller improvements and also is reduced for less even distributions of B versus A trucks.

Table 5 Examples showing the benefits of allowing mixed platoons for three random trucks, each on platooning level A or B, for different B/A distributions and different b/a improvement factors. Backwards compatibility is always assumed here.

Increase of benefit if mix allowed		Distribution B/A				
		10/90	25/75	50/50	75/25	90/10
Improvement factor b/a	1.25	0%	1%	3%	3%	2%
	1.5	0%	2%	6%	6%	3%
	2	1%	5%	11%	10%	5%
	3	1%	4%	9%	7%	3%

If the ordering possibility was considered the numbers would get reduced less compared to Table 5, but it would not look dramatically different.

3.5.4 Recommendation

The above analysis results in two recommendations:

1. Make sure each level of platooning is backwards compatible with previous lower levels.
2. It is unnecessary to allow different levels of platooning within the same platoon.

So for instance if a given truck is compliant to platooning with time gaps down to 0.5 seconds, it should also be able to join a “lower level” platoon with time gaps of 1.0 seconds. However, it is not recommended to spend resources on developing a technology that can handle both 0.5 second gaps and 1.0 second gaps within the same platoon.

4 Corporate cost-benefit and models for sharing

Main authors of this chapter: Björn Mårdberg and Viktor Åkesson

In this chapter, we first describe some models for fuel consumptions and fuel savings with platooning. While the models used in the previous chapters were adapted for estimating both societal and corporate effects, in this chapter we focus on the benefits and costs for companies. Some different ways of sharing the benefits and costs of platooning are then discussed, followed by discussions of the costs of creating platoons and of reordering the vehicles in a platoon.

4.1 Fuel savings

In general, truck manufacturers do not want to reveal absolute numbers on fuel consumptions for their products in a public report. This applies to Volvo and Scania too. However, some numbers on absolute savings due to platooning will be needed in order to perform cost-benefit analysis in Sections 4.3 and 4.4. The way around this problem will be publically available data from the SARTRE and IQFleet projects in combination with an assumed nominal fuel consumption that is meant to be “reasonable” both for a truck such as those used in SARTRE and for a truck such as those used in IQFleet.

4.1.1 Data from previous projects

Figure 2 shows some test results from the SARTRE (SARTRE, 2013) and IQFleet (Johansson, 2014) projects.

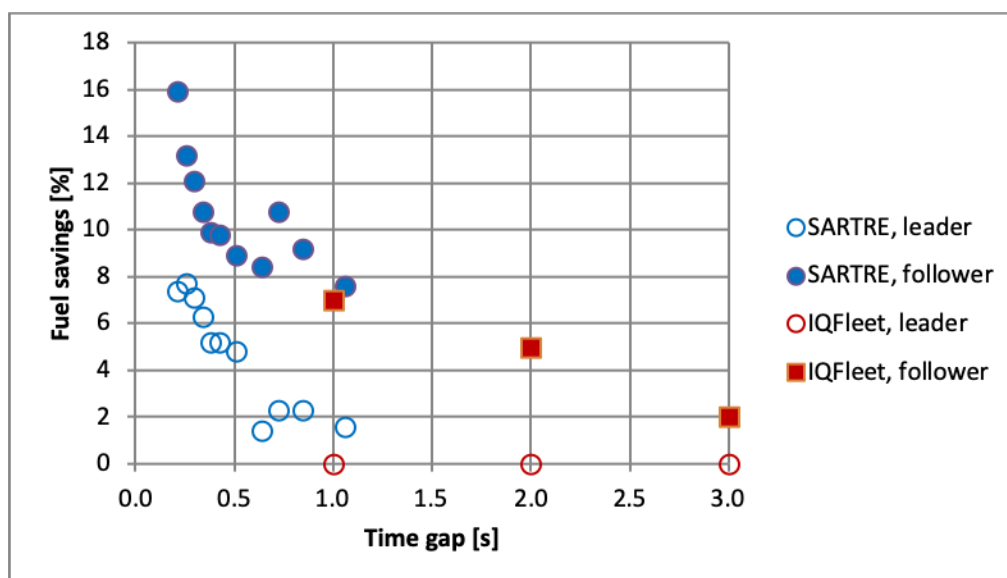


Figure 2 Measured relative fuel savings within SARTRE and IQFleet projects.

Even though the data from the two projects seems well aligned, there were actually significant differences in set-up for each project. Both projects dealt with platooning with

two trucks, but in SARTRE there were sometimes three cars also in the platoon, following the two trucks. In SARTRE there were rigid trucks going at 85 km/h on a test track, while in IQFleet there were tractor-semitrailer combinations following their speed limit of 80 km/h on public road.

4.1.2 Assumptions for Sweden4Platooning

Absolute fuel savings at 80 km/h

As mentioned above, we will assume a “reasonable” absolute fuel consumption, which will be brand neutral. This assumption will be 30 liter/100km at 80 km/h³.

Table 6 Assumed absolute fuel savings while platooning, to be used in further analysis in Sections 4.3 and 4.4.

Time gap [s]	Fuel savings [l/100km]	
	leader	followers
0.8	0.550	2.415
1.0	0.500	2.250
1.2	0.450	2.085
3.0	0.000	0.600

We will also assume absolute fuel savings according to Table 6. Plotting this data together with the data from Figure 2, we get Figure 3, showing that the assumed absolute savings are reasonable.

It should be pointed out that these assumptions must not be extrapolated. For certain the fuel savings for distances gaps longer than three seconds are not negative. Also the fuel savings for shorter distances below 0.8 s is not linear. In this project we settle with

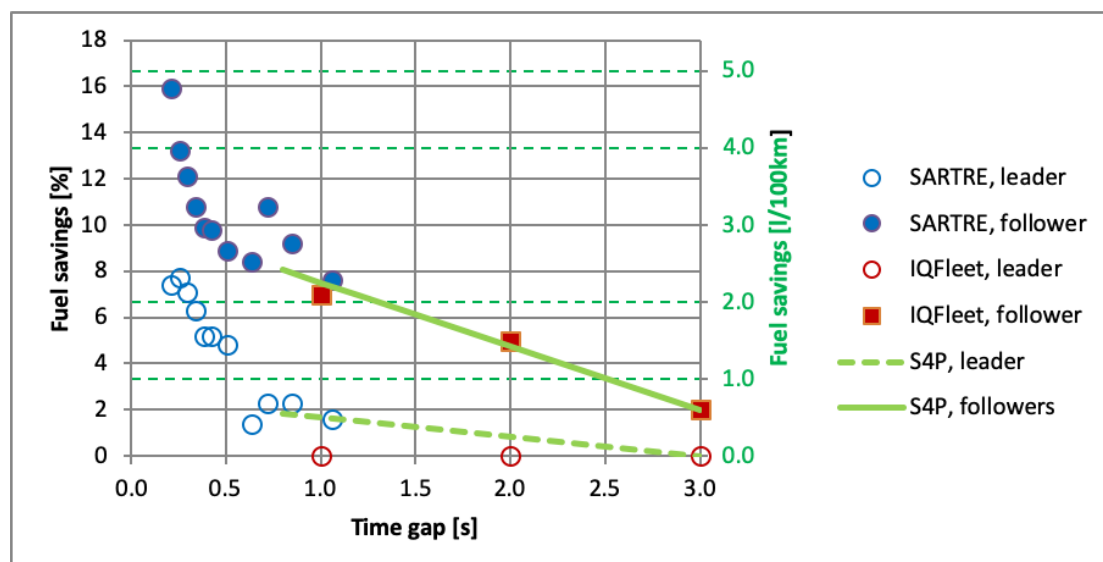


Figure 3 Assumed absolute fuel savings (green lines) for analysis together with measured relative savings from SARTRE and IQFleet project, plotted together assuming a nominal 30 l/100km absolute fuel consumption.

³ Note that this is below the average fuel consumption mentioned in Section 2.5.

describing the fuel savings with a straight line over a limited domain. Outside that interval, no assumptions are made within this project.

Assumed reference

The reference fuel consumption 30 l/100km is assumed to be for an infinite gap. Typical Swedish long-haul situations can almost always be assumed to be free-flow conditions and for those conditions the infinite gap is reasonable as a default assumption. When there is more traffic and gaps between vehicles tend to narrow down even without platooning, the numbers used in Table 6 will sometimes be an overestimation.

Savings depending on following position

Our base assumption is that all followers make the same fuel savings. In general it is believed that in a platoon with three trucks, the middle truck saves more fuel than the tail truck. However, SARTRE and IQFleet projects cannot provide us with data to support this view, and for simplicity we will assume that all followers make the same savings if they have the same gap to the truck in front of them.

Savings depending on vehicle combination length

It will be assumed that absolute fuel savings are not related to vehicle combination length. This is motivated by the thought that you have certain savings “per gap”, regardless of how much vehicle there is before and after this gap.

Savings depending on vehicle weight

It will be assumed that the absolute fuel savings are not related to vehicle weight. This is motivated by the fact that fuel savings while platooning are mostly related to aerodynamics.

Savings depending on other variables

Some other variables that will affect fuel savings while platooning are:

- vehicle speed;
- aerodynamic shape;
- road topography (alignment and horizontal and vertical curvature);
- vehicle speed variations (due to traffic situation);
- weather, wind, road conditions etc...

No assumptions will be made regarding the effect on fuel savings of these variables. The reason for this is simply that none of the research questions selected for S4P WP7 are related to these variables.

4.2 Fuel savings sharing

Since there are differences in fuel saving between different platoon positions, it might be necessary to have a mechanism for compensating for those differences. This section discusses different approaches for such sharing of fuel savings.

4.2.1 Need for sharing of fuel savings

The first question to answer when it comes to compensating for the different fuel savings for different positions in a platoon is:

Will a sharing system help in getting better platooning rates and more total savings?

Sharing of fuel savings will be needed, according to stakeholder interviews performed by DB Schenker. There should be an incentive that every participant in the road train achieves cost savings in a platoon. If the fuel savings for the platoon leader are low compared to the followers, then some way of sharing the savings will be needed. In order for the fuel sharing to be possible, it is also necessary to have some sort of sharing system that distributes the costs among the participants. Chapter 6 analyzes this question further.

4.2.2 Alternatives for sharing savings

Four main alternatives for sharing of fuel savings will be considered:

1. **Payments decided by savings.** Followers pay money and the leaders get money, and there is a system in place to handle this.
2. **Points system.** Followers pay in some way and leaders gain in some way, but using a system where there is no need for money transactions.
3. **Free market.** Uses monetary transactions as for alternative 1 but instead of a common system with predefined compensation rates it would be a system where the leader has the possibility to sell positions in a platoon, if there are buyers, and the price would be settled by the market forces.
4. **Round robin.** The leader position in a platoon rotates among its participants.

Each of these alternatives are discussed in more detail in the following subsections.

4.2.3 System with payments for balancing fuel savings

A method for balancing fuel savings within a platoon will consist of two main steps:

1. Model for quantifying actual fuel savings for each truck;
2. Model for distribution of fuel savings within the platoon.

Each step will be analyzed below. To quantify the actual fuel savings is a real challenge, and we will get back to that in Section 4.2.3.2. First we deal with the distribution model.

4.2.3.1 Distribution of fuel savings

Assuming the fuel savings while platooning are known or estimated, we then have the task of distributing them in a fair way. A model for evening out fuel savings between trucks can be designed in many different ways. There may for instance be a money flow from each follower to the nearest truck in front, or there may be a money flow from each follower to the leader. A follower may pay only in relation to its own fuel savings, or the total number of followers in the platoon may be taken into account. For simplicity, we

will assume that all followers make the same fuel savings, and the models for distribution to be analyzed will be the ones listed in Table 7.

Table 7 Examples of possible distribution models for sharing fuel savings within a platoon. Fuel savings are assumed as x for each follower and zero for the leader. N is the number of trucks in the platoon. k is factor between 0 and 1.

Distribution model		Each follower pays
Move-Forward	MF	x to nearest truck in front
Share-Forward	SF	$x/2$ to nearest truck in front
Share-to-Leader	S2L	$x/2$ to platoon leader
Split-to-Leader	SNL	x/N to platoon leader
Pay-to-Leader	PL	kx to platoon leader
Pay-Nothing	P0	0 (for reference only)

In Table 8 the distribution models (except PL) from Table 7 are compared.

Table 8 Resulting money flows for different distribution models in a platoon of five vehicles. Fuel savings are assumed to be 1.00 monetary units per kilometer for all followers, and all money flows are based on that.

Fuel savings and money flow [money/km]			Vehicles from leader (1) to tail (5)				
			1	2	3	4	5
Assumed fuel savings			0.00	1.00	1.00	1.00	1.00
Distribution model	P0	Money flow	0.00	0.00	0.00	0.00	0.00
		Total savings	0.00	1.00	1.00	1.00	1.00
	MF	Money flow	1.00	0.00	0.00	0.00	-1.00
		Total savings	1.00	1.00	1.00	1.00	0.00
	SF	Money flow	0.50	0.00	0.00	0.00	-0.50
		Total savings	0.50	1.00	1.00	1.00	0.50
	S2L	Money flow	2.00	-0.50	-0.50	-0.50	-0.50
		Total savings	2.00	0.50	0.50	0.50	0.50
	SNL	Money flow	0.80	-0.20	-0.20	-0.20	-0.20
		Total savings	0.80	0.80	0.80	0.80	0.80

The reason for the exclusion of the Pay-to-Leader (PL) model from Table 8 is that this model gives very different results depending on the length of platoon. So instead the PL model is analyzed for different platoon lengths in Table 9.

From Table 7 and Table 8 it is seen that the Split-to-Leader (SNL) model is the only one that will obtain an evened out result for all trucks within a platoon. The Pay-to-Leader (PL) model in Table 9 may otherwise be the most intuitive or the most often proposed model, but depending on which fee k is implemented, there will always be an imbalance between leader and followers for some platoon length. As can be seen in Table 9 a low

fee is bad for the leader if the platoon is short, but a higher fee may seem like a bad deal for the followers if the platoon is longer. If the purpose is to distribute the fuel savings, not for a certain truck to make a profit at the expense of the others, the SNL model will perform better than the PL model. The models could be further refined by allowing the fee k to vary.

Table 9 Resulting money flows for the Pay-to-Leader (PL) distribution model depending on different platoon lengths.

Fuel savings and money flow [money/km]		Vehicles from leader (1) to tail										
		2-platoon		3-trucks-platoon			Five-truck-platoon					
		1	2	1	2	3	1	2	3	4	5	
Assumed savings		0.00	1.00	0.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	
k	0.10	Money flow	0.10	-0.10	0.20	-0.10	-0.10	0.40	-0.10	-0.10	-0.10	-0.10
		Total savings	0.10	0.90	0.20	0.90	0.90	0.40	0.90	0.90	0.90	0.90
			☹️	😊	☹️	😊	😊	☹️	😊	😊	😊	😊
	0.20	Money flow	0.20	-0.20	0.40	-0.20	-0.20	0.80	-0.20	-0.20	-0.20	-0.20
		Total savings	0.20	0.80	0.40	0.80	0.80	0.80	0.80	0.80	0.80	0.80
			😊	😊	😊	😊	😊	😊	😊	😊	😊	😊
	0.50	Money flow	0.50	-0.50	1.00	-0.50	-0.50	2.00	-0.50	-0.50	-0.50	-0.50
		Total savings	0.50	0.50	1.00	0.50	0.50	2.00	0.50	0.50	0.50	0.50
			😊	😊	😊	😊	😊	😊😊	😊	😊	😊	😊

Conclusion on distribution models

Among the analyzed models for distributing fuel savings, the Split-to-Leader (SNL) model is the one that distributes the savings in the most efficient way. With this model there is always a win-win situation for both leader and all followers, and there is always a win-win situation between trucks already in a platoon and one that may join.

Recommendation on distribution model

If a system with payments for sharing fuel savings within a platoon is to be implemented, the recommendation is to use the Split-to-Leader (SNL) model for the distribution.

4.2.3.2 Quantification of fuel savings

Before distributing the fuel savings, the fuel savings must be known, or at least estimated. Knowing the actual fuel consumption is possible with some precision. Knowing what the fuel consumption would be, were the truck not platooning, is not trivial.

A vehicle's fuel savings due to aerodynamics depends on the geometric shape not only of the vehicle but the combination of geometric shapes within the platoon. It also depends on weather, primarily wind conditions. The savings depend on velocity profile, which is affected by the platooning. With uncertainties in all of these values it will be impossible to make any precise estimation of fuel savings in each specific case of platooning. Also, normally there is no reference available, *i.e.*, the same truck will not drive the same route again with the same cargo, in the same weather etc..

Conclusion on fuel savings quantification

To estimate the fuel savings with precision for each truck while platooning is not possible, or at least it is not practical.

Recommendation on fuel savings quantification

Instead of making an attempt to estimate actual fuel savings, the recommendation is that the fuel savings are assumed according to a standard model that is commonly accepted by all platooning partners and service providers.

Proposal for fuel savings quantification

Proposing a standard for calculating fuel savings is not an exact science. The idea is to make it simple enough, so that it can be easily implemented and easily understood, and at the same time make it sufficiently accurate, so that it will seem fair enough for all involved partners and so that no one tries to optimize their behavior in regards to the system rather than for the common good. So, there is a balance to find. In this subsection a proposal for such a standard model is described.

The first part of the standard model is a curve defined by five parameters that describes the fuel saving at 80 km/h for a following truck in a platoon. It is illustrated in Figure 4.

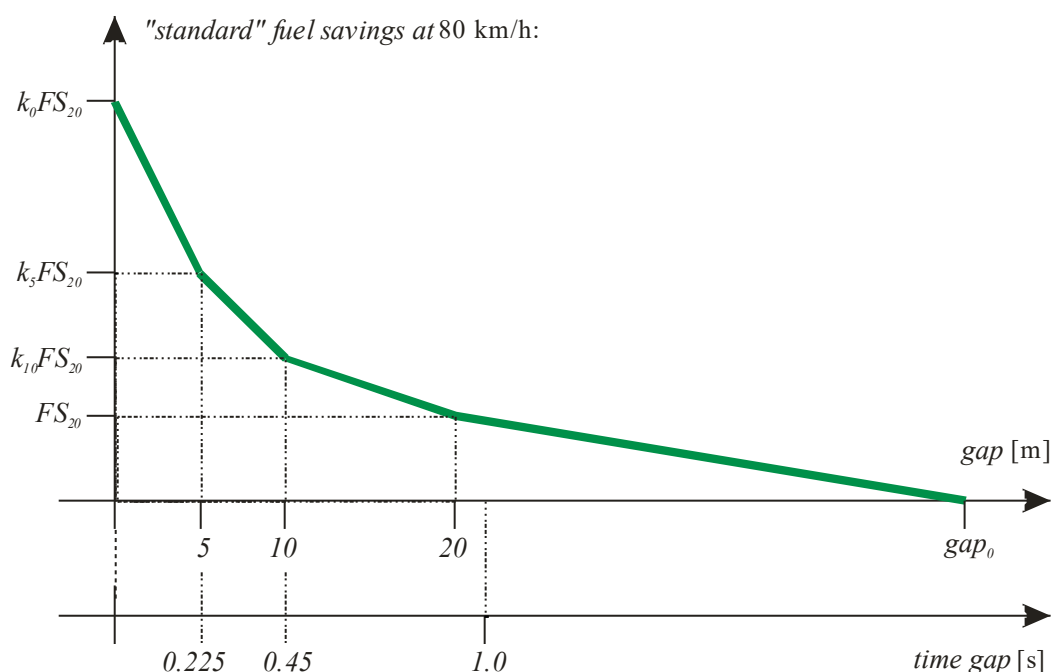


Figure 4 Standard model for describing assumed fuel savings for a truck being follower in a platoon going at 80 km/h. We denote by FS_{20} the fuel savings at a 20 m gap. k_0 , k_5 and k_{10} are factors that define the fuel savings at gaps 0, 5 and 10 meter. The gap_0 parameter is defined as the gap above which the savings are assumed to be zero. The model consists of by four linear segments.

To compensate for vehicle speed, the “standard” savings from Figure 4 are multiplied by a factor $(v/80)^2$. This is done up to the legal speed but not above. The concept is illustrated in Figure 5.

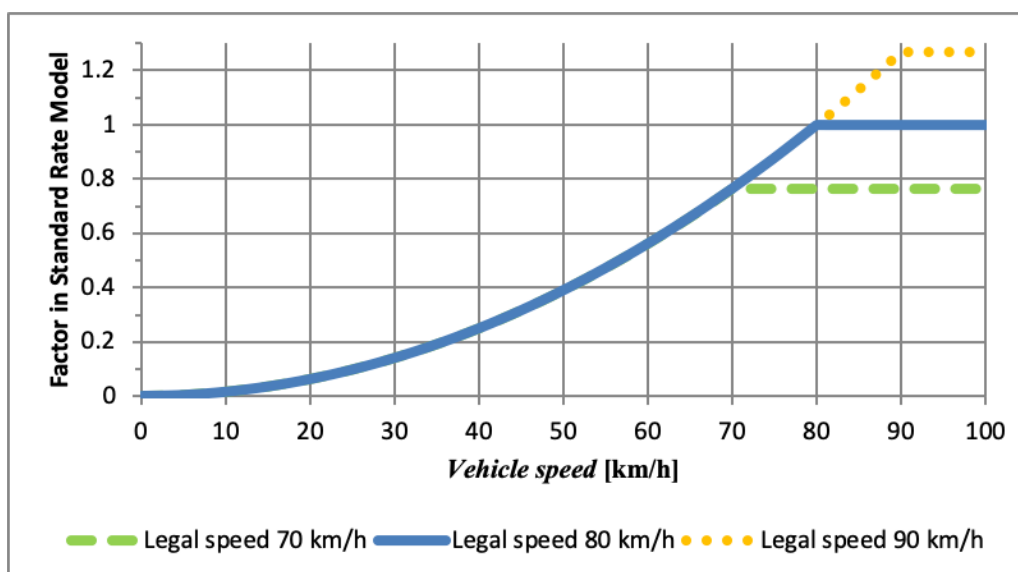


Figure 5 Factor for compensating for vehicle speed in standard model for calculating assumed fuel savings

To take the current price level on fuel into account, the assumed fuel savings are then multiplied by a k_{cost} factor. This factor may be different depending on region, but the other five parameters should be kept the same wherever the compensation system is used.

So far, it has been assumed that all followers are modelled the same way. In case there is a need for modelling in-between-followers differently from the tail truck, the model could easily be extended with five more parameters. If the savings for the lead vehicle are to be modelled too, then either the model could be extended with another five parameters, or else the parameters already in the model could be given values so that the savings relative to the leader are modelled instead of the absolute savings. These and other details can be worked out after deciding on whether or not to use the model described above.

The proposal to start with is to keep the model simple as described above, consisting of only six parameters and simple algebra.

4.2.4 Points system for balancing fuel savings

During the S4P project the idea came up⁴ that instead of sending money between trucks it may be enough to have a points system and decide the order within the platoon based on that. Assume you have a number of trucks ready to enter the motorway from a truck stop. Before leaving, their rankings according to the points system are checked, and the one with the lowest rank takes the lead.

⁴ First mentioned to the project by Sebastian van de Hoef (KTH) at a workshop on April 16th, 2018.

A points system may be designed in several ways. One way would be to make it analogous to the system with payments described in Section 4.2.3 above, only changing the money to some currency of points. On the other hand, if it is accepted to simplify by compensating with points instead of money, then perhaps it is also accepted to simplify the calculations. The proposal described below will be based on the assumption that you can make it simpler in both these ways.

4.2.4.1 Proposal for points system

A points system for compensating for different fuel savings within a platoon is proposed as follows:

- For a platoon with two trucks, the follower pays 1 point per km, and the leader receives 1 point per km;
- For longer platoons, the followers pay $2/N$ points per km each, where N is the platoon length, and the leader receives the sum of those points.
- When a platoon is formed or re-formed the trucks are ordered according to their current points, lowest score first;
- Points are shared only when certain constraints on vehicle speed and gap lengths are fulfilled.

The constraints for when to count points would need to be accepted by all parties, but a proposal to start with is: vehicle speed at least 70 km/h and time gap maximum 1.2 s.

If we compare with the payments system described in Section 4.2.3, the distribution system here for the points system is identical to the recommended SNL model. The difference is the quantification system, which for the points system is much more simple and consequently has a lower correlation with real savings. It would be possible to have it more advanced for the points system too, but the proposal here is to start simple.

4.2.5 Market system for compensating for fuel savings

The third variant to be considered for sharing fuel savings is to let leaders put a price on platoon positions and simply let the market decide.

For this alternative it would be left to the market forces to drive the evolution towards one or many systems that will be good enough for the involved partners. You cannot expect 100% fairness from a market system, and sometimes even if two trucks are close to each other and would benefit from platooning, perhaps they will not reach a deal, and thus there will be no platooning. A benefit with the market is its flexibility. Prices can change at any time and a new system can be launched without first reaching a broad agreement with all who might use the system. It could also handle the fact that different trucks will get different levels of saving, and they can take this into account when bidding on platoon positions, without the need to communicate the actual saving estimates.

4.2.6 Round robin

The fourth and final alternative to consider is the round robin alternative.

A method for rotating the leader could possibly simplify things compared to the sharing systems described above, but creating a system for coordinating such a behavior would also face some challenges. As long as there is a fixed number of trucks platooning the same distance, it is easy to decide when to switch leaders, but if trucks are to be able to join and leave along the way, then it is not trivial. It is shown in Section 4.4 that the process for switching leaders would not cost much for the platoon participants, but the cost for other road users also needs to be considered (compare Section 3.4). A system for coordinating the rotation of leaders within a platoon is out of scope for the S4P project.

One alternative is that a round robin culture will emerge spontaneously among the drivers. If the first generation of platooning products from truck manufacturers can be purchased without the fuel savings sharing option, then time will tell whether such a driving culture will emerge.

4.2.7 Comparison of methods for fuel savings sharing

Four alternatives for sharing fuel savings have been described above. Each has its pros and cons. The money system as described in Section 4.2.3 may be the most fair alternative, but also, even if meant to be simple, still the most complex. The points system may be a bit simpler, and still fair enough. The market alternative gives room for flexibility, but there is always some uncertainty whether two trucks who could platoon together also will reach the deal needed for the platooning to take place. The round robin case has not been analyzed enough to compare with the others. We chose not to propose a system based method related to this variant, but it cannot be ruled out that a round robin culture will emerge without any system support. The potential of each of the first three variants is analyzed in Section 5.2. In Table 10 we give a brief comparison of these three.

Table 10 Pros and cons for each of three fuel savings systems. The money system is assumed to be with standardized fuel savings calculations, whereas the points system is assumed to be without fuel savings calculations, only simple constraints for when to count

	Money	Points	Market
Pros	fair	simple	flexible
Cons	complex	insufficient balancing?	less platooning?

A final comment is that more variants are possible. For instance, for a system with money changing hands, you could still have simple constraints for when to pay (as in Section 4.2.4.1) instead of the assumed fuel savings (as in Section 4.2.3.2).

4.2.8 Recommendation on fuel savings sharing

Based on the simple analysis above and also the analysis in Section 5.2, we make the following recommendations:

- For balancing of fuel savings between platooning participants, start with a points system. The points system as described in Section 4.2.4.1 is a starting point. The followers pay $2/N$ points per kilometer to the leader. When forming a new platoon, the truck with the lowest score takes the lead.

- If a points system is found to be insufficient or not fair enough, then consider one or both of the following:
 - Real money transactions instead of only points. Use the Split-to-Leader (SNL) model as distribution model.
 - A model for quantifying savings. Use a commonly accepted standard model instead of attempting to estimate actual savings. The model described in Section 4.2.3.2 is a starting point.

4.3 Cost of creating platoons

One of the challenges with platooning is to get a number of trucks to the same position at the same time to be able to form a platoon. Unless they are scheduled to leave from the same logistics center at the same time or they just happen to be right after each other on the motorway by chance, some synchronization needs to be done. From a given truck's perspective, there are the following possibilities to adjust plans in order to enable platooning:

- Wait for one or more trucks to platoon with before entering the motorway;
- Slow down in order for another truck or a platoon to catch up;
- Take a detour to catch another truck or platoon.

Also there are combinations of these actions. If for instance the route is adjusted, then speed adjustments are probably needed as well.

We already have a view of the benefits of platooning while actually performing the platooning. If however plans need to be adjusted in some way in order to enable platooning, this comes with some cost. In the case of taking a detour this is obvious. The extra kilometers will result in extra consumed fuel. The two other actions also come with some cost, "time is money", even though they may not be as easy to quantify.

In order to quantify lost time due to coordination prior to platooning, it will be assumed that time has a price. In a specific case the cost for waiting may be anything from zero to very high. If there happens to be enough room in the schedule, the cost for waiting a few minutes may be zero, but if those few minutes are just what it takes to cause a late delivery or missing a ferry, the cost may be high. The aim here is not to create some rule to be taken as absolute truth. Instead the aim is to put the benefits from platooning in perspective and create a general understanding for how much coordination efforts it may be worth taking. For that purpose it seems reasonable to set a certain price on time and include this in the equation when judging a certain platooning opportunity. Additionally, costs for changes in planning for the logistics service provider are not considered. Since most terminal to terminal departures are fixed in order to optimize the total logistics chain, we would need to consider changes in blue collar schedules and such. This could be further analyzed in future research.

4.3.1 Cost-benefit analysis for waiting

The first option for platoon formation is that a vehicle waits for another one. This subsection analyzes what costs and benefits are associated with waiting.

4.3.1.1 The cost side

Operating costs for trucks are given in Table 11, which is based on Table 14.3 in ASEK 6.1 (Trafikverket, 2018). The data originally comes from The Swedish Association for Road Transport Companies and is based on corporate costs per operating hour. Societal costs associated with CO₂ and other exhausts are here ignored.

Table 11 Time dependent operating cost for trucks according to assumptions from Trafikverket. Numbers for total weight (including max cargo) either 40 tonne or 60 tonne.

Cost item	Operating cost [SEK/h]	
	40 tonne	60 tonne
Driver	235	244
Insurance, taxes, garage, mobile phone, etc...	36	38
Depreciation	26	29
Capital cost	16	18
Total	314	328

In the following calculations, when not stated otherwise, the numbers for the 40 tonne alternative will be used.

4.3.1.2 The benefit side

There may be other benefits with platooning related to improved safety or reduced congestions, but here only the fuel savings are considered. Assumed fuel savings are given in Table 12.

Table 12 Fuel savings while platooning, translated into money. The columns for leader and follower refers to when there is no system for balancing savings, whereas the columns for 2 or 3 trucks assume that such a system for sharing savings between trucks is in place

Time gap [s]	Fuel savings [SEK/100km]			
	leader	followers	2 trucks	3 trucks
0.8	7.5	33.0	20.3	24.5
1.0	6.8	30.8	18.8	22.8
1.2	6.2	28.5	17.3	21.1

Diesel price: 13.670

The next thing to assume is price on diesel fuel. On the 17th of May in 2019, both Preem and OKQ8 charged 17.09 SEK/liter including VAT. Deducting 25% VAT gives 13.67 SEK/liter, and this will be the assumed price on diesel fuel for further analysis.

Combining the fuel savings data from Table 6 above with the assumed diesel price gives the benefits translated into money as in Table 12.

4.3.1.3 Cost versus benefit for waiting

Now that both the cost and the benefits are expressed on the money scale, they can be weighed against each other. In Table 13 the benefits from 100 kilometers of platooning is expressed as time worth waiting in minutes.

Table 13 Waiting times corresponding to the benefits from 100 km of platooning

Time gap s	Waiting time [min] equivalent to 100 km platooning			
	leader	followers	2 trucks	3 trucks
0.8	1.4	6.3	3.9	4.7
1.0	1.3	5.9	3.6	4.3
1.2	1.2	5.4	3.3	4.0
3.0	0.0	1.6	0.8	1.0

So, for instance, assuming a system for balancing fuel savings between trucks, the benefits from platooning 100 kilometers with another truck, keeping a 1.0 second gap, corresponds to the cost for waiting 3.6 minutes for that other truck before entering the motorway from a truck stop.

4.3.2 Cost-benefit analysis for slowing down

The second option for platoon formation is that a vehicle continues driving but at a lower speed in order for another one to catch up and form a platoon. This subsection analyzes what costs and benefits are associated with slowing down. We ignore the possible costs and benefits that increasing the size of the platoon brings to the platoon or truck that is following behind.

4.3.2.1 The cost side

The cost for slowing down that will be considered is the cost for later arrival. Assuming a potential platooning partner is traveling at 80 km/h some distance behind you, the cost for later arrival as in Table 11 can be translated into cost for initial gap as in Table 14.

Table 14 Cost for later arrival due to slowing down so that a truck at a certain distance behind can catch up. Cost is given both per minute of later arrival (translated from Table 11) and per kilometer of initial gap to the truck behind.

Vehicle combination	Cost for later arrival	
	SEK/min	SEK/km
40 tonne	5.23	3.93
60 tonne	5.47	4.10

For further analysis below we will use the numbers for the 40 tonne combination.

If you slow down your truck for only a short while and then have to accelerate it back to 80 km/h, you will lose more during that transient than you will save due to lower air drag. This will not be considered in our analysis here. The vehicle dynamics and energy simulations that would have been needed for this have not been made. Instead this will be a source of error to keep in mind.

4.3.2.2 The benefit side

On the benefit side there are obviously the fuel savings during the platooning that will occur after some distance. During the platooning these savings will be according to Table

12. There are two more aspects to consider however, when calculating the benefits, and they are related to the period while driving slower. One aspect is the fuel savings that are made during the slow driving period. The other aspect is that the slow driving will be for a certain distance, and the longer this distance, the less distance remaining for the platooning.

The estimated fuel savings during the period when our truck is going slower than 80 km/h will be based on the following two simplified assumptions: one third of the fuel consumption at 80 km/h is related to aerodynamics, and this part is reduced by the square of the vehicle speed when going at a lower speed. Table 15 gives some examples of resulting savings per kilometer given these assumptions.

Table 15 Continuous fuel savings while going slower.

Low speed km/h	Low speed fuel savings		
	%	l/100km	SEK/km
78	1.6	0.5	0.07
75	4.0	1.2	0.17
70	7.8	2.3	0.32
60	15	4.4	0.60
50	20	6.1	0.83

To produce the numbers in the SEK/km column in Table 15, we used the price on diesel that was assumed in section 4.3.1.2. On the subsequent platooning part of the journey, we have the worth of fuel savings according to Table 12. For the rest of the analysis here only the 1.0 s gap will be considered. No vehicle speeds below 70 km/h were included. This is in line with what was assumed in Section 2.2.

When putting the savings from both the initial slow driving period and the subsequent platooning together, we get examples of total savings for the truck slowing down as in Table 16.

Table 16 Examples of fuel savings for the truck that slows down during first the slow-driving part, then the platooning part of the trip and for the total, which is assumed to be 100 km. Initial distance to the truck or platoon coming from behind is assumed as 1 km. Time gap during platooning is assumed to be 1.0 s. The columns "leader" and "follower" show the savings for the slowing down-truck when it assumes that role in the platoon and there is no system for balancing savings, while the columns "2 trucks" and "3 trucks" show the savings when such a system is in place.

Vehicle speed km/h	Part of trip	Distance	Fuel savings [SEK]			
		km	leader	followers	2 trucks	3 trucks
78	low speed	39	2.6	2.6	2.6	2.6
	platooning	61	4.2	18.8	11.5	13.9
	total	100	6.8	21.4	14.1	16.5
75	low speed	15	2.5	2.5	2.5	2.5
	platooning	85	5.8	26.1	16.0	19.4
	total	100	8.3	28.6	18.5	21.8
70	low speed	7	2.2	2.2	2.2	2.2
	platooning	93	6.4	28.6	17.5	21.2
	total	100	8.6	30.8	19.7	23.4

The numbers in Table 16 indicate that the total fuel savings get larger for the largest decrease of vehicle speed during the phase when waiting for the other truck or platoon to catch up. We will not go through the calculations here, but it can be shown that for the assumptions we have made, the optimum speed for maximizing fuel savings would actually be below 70 km/h, which was the limit we set in Section 2.2. (For 1.0 s gap and considering the 2 or 3 trucks alternatives with balancing system included, the optimal speed during the slow-driving period will be approximately 60 km/h.) For the remainder of the slowing down analysis, 70 km/h will be the assumed slow speed.

4.3.2.3 Cost versus benefit for slowing down to enable platooning

Initial gap km	Cost-benefit [SEK]					
			leader	followers	2 trucks	3 trucks
1	low speed	7 km +	2.2	2.2	2.2	2.2
	platooning	93 km +	6.4	28.6	17.5	21.2
	delay	-	3.9	3.9	3.9	3.9
	total	100 km =	4.7	26.9	15.8	19.5
2	low speed	14 km +	4.5	4.5	4.5	4.5
	platooning	86 km +	5.9	26.5	16.2	19.6
	delay	-	7.9	7.9	7.9	7.9
	total	100 km =	2.5	23.1	12.8	16.2
5	low speed	35 km +	11.2	11.2	11.2	11.2
	platooning	65 km +	4.4	20.0	12.2	14.8
	delay	-	19.6	19.6	19.6	19.6
	total	100 km =	-4.0	11.6	3.8	6.4
10	low speed	70 km +	11.2	11.2	11.2	11.2
	platooning	30 km +	2.1	9.2	5.6	6.8
	delay	-	39.3	39.3	39.3	39.3
	total	100 km =	-26.0	-18.8	-22.4	-21.2

Table 17 Cost-benefit calculations for a few scenarios of first slowing down and then platooning with one or two trucks coming from behind. Truck speed during the slow period is assumed as 70 km/h and time gap while platooning is assumed as 1.0 s.

If we combine the benefits calculated above with the delay cost from Section 0, we get examples of total gains for the truck that slows down for a few different initial gaps as in Table 17.

One reflection from the numbers of Table 17 is that for a longer initial gap, the fuel savings from the slow-driving period increases compared to the savings during the platooning, but on the other hand the delay cost increases too, and in the end it is the delay cost that in makes the equation impossible for longer initial gaps. In Figure 6 this is illustrated graphically.

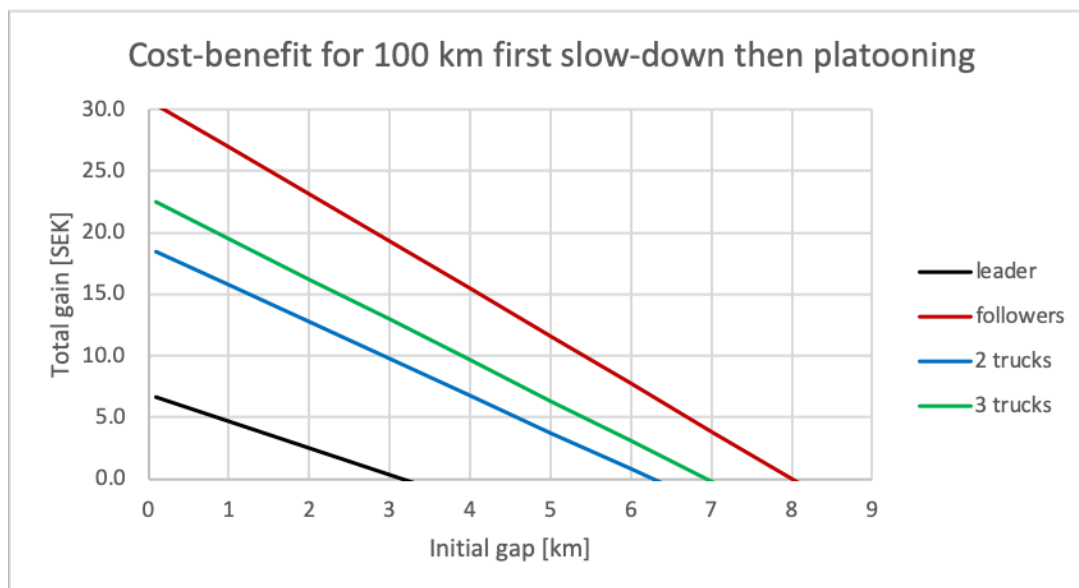


Figure 6 Total gains for a scenario of first slowing down to let one or two trucks catch up and then perform platooning. Vehicle speed during the slow period is assumed as 70 km/h and time gap during the platooning session is assumed as 1.0 s.

In Figure 6 you can read out maximum initial gaps for a slow-down in order to later enable platooning that will be meaningful. They can be read out from where the lines cross the horizontal axis. They are also summarized in Table 18.

Table 18 Break even initial gaps for a scenario of first slowing down and then do platooning with one or two trucks coming from behind. Vehicle speed during the slow period is assumed as 70 km/h and time gap during the platooning session is assumed to be 1.0 s.

Break-even initial gap [km]			
leader	followers	2 trucks	3 trucks
3.2	8.0	6.3	7.0

So, for instance, if you have 100 kilometers left of your trip, and there is a truck within three kilometers behind, which is willing to do platooning the remaining distance with you, it will be worth slowing down and waiting for that truck, even if you need to become the leader and there is no balancing system in place. With a system in place for balancing the worth of fuel savings, it would be beneficial even if that other truck was up to six kilometers behind.

In the case where you are slowing down to form a truck with a single following truck, that truck too will get benefits from the platooning. If a system for sharing the costs of creating the platoon (*i.e.*, the delay) were in place, this could make it beneficial to slow down in more cases.

4.3.3 Cost-benefit analysis for detours

Suppose there are two alternative routes from A to B. One is the shortest and normally the best for both time and fuel consumption. The other one is slightly longer, but on this

particular occasion there happens to be an opportunity to platoon for some part it. So, which route to choose?

4.3.3.1 The cost side

There are two costs associated with taking a longer route. The first cost is the delay cost as given by Table 11. The second cost is the extra fuel consumed by driving a longer distance. Table 19 gives a few examples of the cost for going one extra kilometer.

Table 19 Examples of cost for going one extra kilometer, different results depending on nominal fuel consumption. Delay cost is 314 SEK/h and diesel price is 13.67 SEK/l.

Fuel consumption l/100km	Cost for 1 km detour [SEK]		
	Delay time	Extra fuel	Total
30	0.0	0.6	0.6
40	0.0	0.8	0.9
50	0.0	1.1	1.1

Nominal fuel consumption may be very different depending on type of truck combination. This is the reason for three different examples in Table 19. As an example 40 liter/100km may be reasonable for a fully loaded Eurocombination, and as another example 50 liter/100km could be the fuel consumption for a fully loaded Nordic combination, and 30 liter/100km may be the fuel consumption for a truck carrying lightweight cargo. The delay cost is based on the 40 tonne alternative in Table 11. Price for diesel is assumed the same 13.67 SEK/liter as used in section 4.3.1.2.

4.3.3.2 The benefit side

The benefit side here is simply the fuel savings during the platooning. These will be the same as in Table 12. The detour analysis will be limited to the 1.0 s gap.

4.3.3.3 Cost-benefit for detour

Now that both cost and benefits for detours have been put on the money scale, they can also be compared to each other as in Table 20.

Table 20 Detour distances corresponding to the benefits from 100 km of platooning.

Nominal fuel consumption l/100km	Extra distance [km] equivalent to 100 km platooning			
	leader	followers	2 trucks	3 trucks
30	0.9	3.8	2.3	2.8
40	0.7	3.3	2.0	2.4
50	0.6	2.9	1.7	2.1

What Table 20 basically says is that an opportunity to do for instance 100 km of platooning is only worth a few extra kilometers due to adjusting the route, around two kilometers for the alternative when you hook up with one other truck and assuming a system for balancing savings is in place.

4.3.4 Conclusion on cost for creating platoons

Looking at the numbers for each coordination method described above, the following conclusions can be made:

- Waiting a few minutes in order to enable a couple of hundred kilometers of platooning seems reasonable.
- Slowing down to let another truck a few kilometers behind catch up, in order to afterwards being able to do a couple of hundred kilometers of platooning also seems reasonable, at least for the involved trucks. Whether it is reasonable for other road users having to deal with a truck going significantly slower for some distance is another question.
- Finding an alternative route, which is only a few kilometers longer, and that way being able to do some platooning, does not seem like something that will happen often.

4.3.4.1 Discussion on delay cost

Cost for later arrival, as assumed in Table 11 is far from to be taken as indisputable truth. However, for a hauling company that is considering some investment in platooning technology, it will be very easy to rescale the results from above to get them in line with their own knowledge regarding their time cost. In a specific situation when a driver is to decide whether to go or wait, there will most likely be more relevant information at hand for the time cost at that specific time.

4.4 Reordering

In this section, we briefly discuss the internal costs associated with reordering of a platoon. In addition to these, there could also be external, safety and level of service costs (compare Sections 3.3 and 3.4) associated with a reordering, in particular in medium or heavy traffic flows.

The order of trucks within a platoon can be based on different criteria:

- **Energy efficiency:** To minimize energy consumption, previous work (Wahnström, 2015) and (Jeber, 2015) indicate that putting the heavier combination first is the best alternative.
- **Safety:** If the involved trucks have different braking capabilities, and if these are known, then the order may be to put the slowest braking truck first. One comment here is that if the ABS systems works perfectly, then brake performance is not limited by the vehicle weight. Instead it is limited by the friction coefficient between road and tires, so differences between vehicles will depend on quality differences and aging of tires, which is probably not trivial to keep track of.
- **Balancing of benefits:** If order is based on a points system for balancing fuel savings, then the truck with the largest debt from previous platooning without being a leader can be put in the lead, see Section 4.2.4. You can also have a procedure where the trucks take turns in leading, for instance two trucks may switch order after half way.

The list can be made longer (to include also, for instance, societal effects other than safety), and random order is also a possibility.

Here we will not dig into the question on how to select a certain order and instead only look at the cost for reordering a platoon while on the road.

The analysis will be focused on fuel consumption, time lost during a reordering phase, and on average cost on platoon level. One simplification will be that vehicle dynamics is not considered, so impact on fuel consumption due to transients will not be captured.

4.4.1 Cost for reordering

The following aspects will be considered when estimating the internal cost for a reordering action:

- later arrival;
- distance without platooning during the reordering process;
- fuel savings due to lower vehicle speed during the reordering process.

We start looking at a scenario with two platooning trucks that will switch order. The process we assume is that the following truck goes out in the left lane, and at the same time the lead truck slows down (possibly by coasting without using the vehicle brakes) to a certain vehicle speed, and continues at the slower pace while being overtaken by the other truck. When the overtaking truck is 1.0 s ahead of the overtaken truck, it goes back into the right lane, and the overtaken truck goes back to the same speed as the leader. As mentioned above, vehicle dynamics is excluded from the analysis, and time for deceleration and acceleration is not considered. The discussion here also ignores the level of service effects of reordering (see Section 3.4). This is a simplification.

The later arrival corresponds to a distance, which is the sum of one vehicle length and one platooning gap, so for instance 16.5 meter for a Eurocombination plus 22.2 meter for a 1.0 second gap at 80 km/h, total 38.7 meter or 1.7 second.

The distance without platooning is related to the time consumed by the reordering phase. Time and distance for this will depend on how much the overtaken truck is slowing down. Some examples for one Eurocombination overtaking another is shown in Table 21.

The fuel savings due to the overtaken truck driving slower during the reordering process are a bit more uncertain. Some estimates are given in Table 21. They are based on the same assumptions regarding fuel consumption in relation to vehicle speed as were used in section 4.3.2.2. One third of the fuel consumption comes from aerodynamic drag at 80 km/h, and this part is reduced by the square of the vehicle speed when going slower.

Table 21 Cost for one Eurocombination overtaking another during platooning. The cost for late arrival has been distributed to both vehicles even though it is only the overtaken truck that is delayed. Vehicle lengths are assumed as 16.5 m and platooning gap is assumed to be 1.0s. In the rightmost column the total cost for the reordering process is translated into equivalent distance of platooning for the two trucks.

Slow speed	Later arrival		Distance w/o platooning		Fuel savings while driving slower			Total	Equivalent platooning distance
					overtaken truck		both trucks		
km/h	s	SEK/truck	km	SEK/truck	ml diesel	SEK	SEK/truck	SEK/truck	km
79	1.7	0.15	6.2	1.16	20	0.28	0.14	1.18	6.3
78	1.7	0.15	3.1	0.57	25	0.34	0.17	0.56	3.0
75	1.7	0.15	1.2	0.23	23	0.32	0.16	0.22	1.2
70	1.7	0.15	0.6	0.11	21	0.29	0.14	0.12	0.6

Vehicle dynamics and how energy consumptions is affected during transients are not considered, so this makes the numbers for the lower speeds more uncertain.

The numbers in Table 21 indicate that the more the overtaken truck slows down, the less the reordering process will cost. This may be an oversimplification though. The more the overtaken truck is slowed down, the more important dynamic effects will be, which were excluded in the calculations. It may even be that the energy consumption during the transients for lower slow speeds would outweigh the savings due to lower speed. The simple investigation done here will simply not give us all the answers.

If we instead had one Nordic combination overtaking another Nordic combination, we would get slightly higher numbers compared to Table 21, since with longer vehicles the reordering process will consume a bit more time and kilometers. The differences would be small however, and we will not show the numbers here.

For a platoon with three or more trucks there are more options for reordering, but if we only look at the scenario where the last truck moves up to first position while the others slow down, we get numbers as in Table 22.

Moving a truck from last to first position obviously will consume more time and distance if the platoon is longer, but as the numbers in Table 22 show, per truck such a reordering will cost less for the longer platoon.

Table 22 Cost for one truck moving from last to first position in a platoon with 2 to 4 Eurocombinations. In the rightmost column this cost is translated into equivalent platooning distance. During the overtaking procedure the overtaken trucks were assumed to go at 75 km/h while the overtaking truck travels at 80 km/h. Platooning gap is assumed as 1.0 s.

Platoon length	Scenario	Total overtaking cost	
		SEK/truck	km
2 Eurocombinations	One truck overtaking 1 truck	0.22	1.2
3 Eurocombinations	One truck overtaking 2 trucks	0.18	0.8
4 Eurocombinations	One truck overtaking 3 trucks	0.17	0.7

On the other hand, for a longer platoon, it may be needed to do the reordering more often. If two trucks do 300 km platooning together they may switch order after 150 km to make it even, but if three trucks platoon the same distance, they would need to do two reorderings, one after 100 km and one after 200 km, to even out the savings.

4.4.2 Conclusions on reordering

The main conclusion is that the cost for a reordering action is very small for the involved trucks. So for instance a system or a driving culture where the trucks take turns in leading, like bicycle racers do, could be a possibility. The reordering occasions would not have to cost too much.

Another question is how much a reordering procedure costs for other road users. This question is analyzed in Section 3.4.

5 Platoon formation

Main authors of this chapter: Jakob Axelsson, Alexander Johansson, Pontus Svenson

In this chapter, we tackle the issue of how to ensure that platoons can be formed. Two cases are analysed. In Section 5.1, we investigate the dependence of energy and transport efficiency on different ways of forming platoons on the road, while Section 5.2 uses game theory to study the problem of how to form platoons at transport hubs.

5.1 Dynamic on-road formation

One scenario for platoon formation is when the trucks are already on the road, and they team up in platoons when opportunities emerge. In this section, it is studied how different strategies for finding partners affect key business metrics.

5.1.1 Emergent properties and metrics

In order to investigate the effect of different platooning strategies on the platooning rate, simulation of platooning on a road network sharing statistical properties with the Swedish highway network were performed. The benefits of platooning were measured by computing the energy efficiency (*i.e.*, fuel saving), while the costs were measured by determining the transport efficiency (*i.e.*, waiting times for the trucks waiting to form a platoon).

Energy and transport efficiency represent key *emergent properties* of platooning. The overall energy efficiency, or fuel consumption for conventional vehicles, is a direct consequence of how much time is spent in platooning compared to solitary driving. The indicator to use is thus the proportion of total time that vehicles drive in groups with other vehicles, denoted by ϕ . $\phi = 0$ means that no platooning takes place, and $\phi = 1$ that all vehicles always drive in platoons.

Transport efficiency is not affected by the actual platooning, but by the formation process, since vehicles sometimes will choose to wait for others in order to be able to form a platoon instead of driving alone. In practice, the cost of waiting includes the reduced utilization rate of the vehicles, the salary cost for having drivers wait, and the delayed delivery of the goods (compare Table 11 above). The indicator τ is the proportion of time that vehicles move, where $\tau = 0$ means that all vehicles just wait all the time, while $\tau = 1$ when no vehicles ever wait.

ϕ and τ are indicators of the efficiency of platooning. As a reference, in the situation when no vehicles are equipped for platooning, $\phi = 0$ since no vehicles platoon, and $\tau = 1$ since vehicles never wait for each other. We also measure the average waiting time for trucks in the simulations.

It is interesting to investigate how certain factors influence the efficiency metrics. This includes properties of the road network and traffic intensities, since it can be assumed that platooning will require a certain traffic intensity to be meaningful and hence will only be applicable at certain parts of the road network. At the same time, platooning will not work well if the traffic intensity is too high, because that will lead to congestion where

the reduced speed minimizes the fuel saving potential, and also makes it difficult to form platoons. Conversely, there could be other reasons, such as safety, that exclude *a priori* certain types of roads from platooning, *e.g.*, restricting it to only motorways to allow other vehicles to safely pass a truck platoon as described in Section 2.2 above. The proportion of vehicles equipped with platooning will be decisive for the ability to form platoons. In the graph presenting results below, the parameter m indicates the number of vehicles that are able to platoon.

5.1.2 Simulation model

The simulations used randomly generated road networks that share statistical properties with the Swedish 110 km/h and 120 km/h motorway network. The roads are represented by networks where nodes correspond to possible formation points for the platoons (*e.g.*, rest areas). The average density of truck combinations in the Swedish motorway network is about 0.5 per km of road, which gives us a relation between the size of the road network simulation and the number of truck combinations to use in the simulation. In the simulations, road network corresponding in size to about 10% of the total Swedish motorway network were used. The distances between formation points was taken to be a Poissonian distribution with mean 5 (adding 1 to the result to ensure positive distances).

Simulations were performed over several different road networks with some variation in size. The number of trucks simulated was also varied, using the average number 0.5 trucks per km given above as a baseline (denoted by $m = 1$). Simulation were done for number of trucks a multiple of this baseline figure from 0.1 up to 3. This enables us to simulate the effect of varying amounts of platooning-equipped trucks.

Each truck randomly generates a plan for its next time-steps. If two or more trucks are at the same node at the same time and all will continue to the next node in the next time-step (*i.e.*, they have the same plan for the next time-step), they will platoon in the next time-step.

Platoons are thus formed spontaneously when trucks are at the same place at the same time. However, trucks can facilitate the formation of platoon by choosing to wait for other trucks to arrive at their node. The effect of different strategies for determining whether to wait or not is the main variation in the simulations. The strategies use information about the other trucks, which necessitates a mediating service that can provide such information (see Chapter 6). We describe the different strategies used in the next section along with the results.

5.1.3 Simulation results

The baseline to which we compare all simulations is the case where no coordination between trucks take place, but each truck randomly decides to wait in each time-step. This is the speculative waiting strategy. We denote the probability with which a truck waits with p and use values from 0 to 0.8 for p .

In the baseline no information is exchanged between the vehicles in order to facilitate the formation of platoons. This puts severe limitations on what effects can be achieved since there is no way for a truck to predict whether a partner will be available or not. To remedy this, one could let vehicles announce their current position and route plans to each other and let this influence the decision whether to wait or not.

Note that this adds a requirement that the platooning SoS must include an infrastructure for this communication. Since potentially a vehicle may exchange information with any other vehicle, the short-range radio used for vehicle-to-vehicle communication will not suffice, and instead cellular communication must be employed. Most likely, it will also include a centralized mediator that dispatches the information between vehicles, since otherwise all vehicles would need to communicate with all other vehicles.

The information that can be communicated is current position and plans of the vehicles. Letting the plan length of vehicles be L , we performed simulations that communicated with all other vehicles at a distance $L - l_p$. The term l_p was introduced to be able to simulate different requirements on the length of platooning that is desired: a vehicle will wait if there is another vehicle with which it can platoon for l_p time-steps.

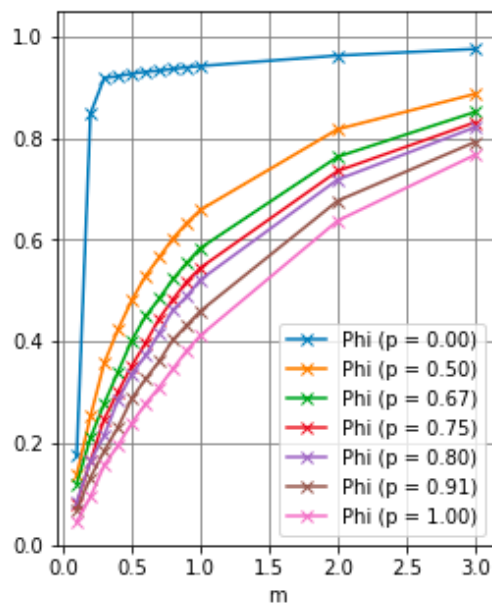


Figure 7 The energy efficiency (ϕ) as a function of number of platooning-equipped vehicles (m) for the base-case of stochastic platooning: each vehicle waits with probability p (the different curves) in each time-step.

Results of simulations for the base-case of opportunistic platooning are shown in Figure 7, while Figure 8 ($l_p = 1$) and Figure 9 ($l_p = 2$) show results for the intelligent decision function that waits up to $L - l_p$ time-steps if it is possible to platoon for at least l_p time-steps. In the latter cases, simulations were done for several different values of L , corresponding to the different curves in the figures.

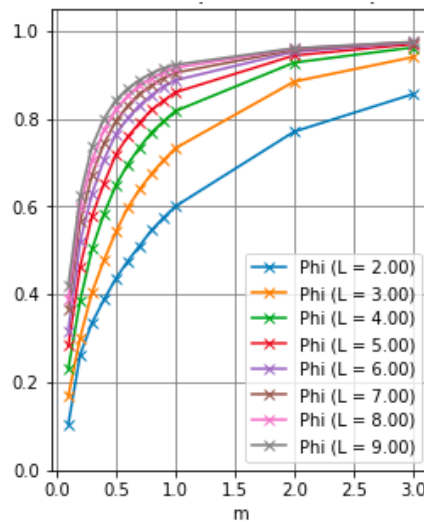


Figure 8 The energy efficiency (ϕ) as a function of number of platooning-equipped vehicles (m) for the planned decision function with $l_p = 1$ with different plan lengths (L).

It is clearly seen that exchanging information about plans has a large benefit in increasing platooning rate and bounding the cost, and the inclusion of a coordination mechanism in the SoS is thus needed. In particular, the effects are most significant when there is a small number of platooning-equipped vehicles and the coordination is therefore particularly important when platooning is first introduced since there is then only a small number of equipped vehicles in service.

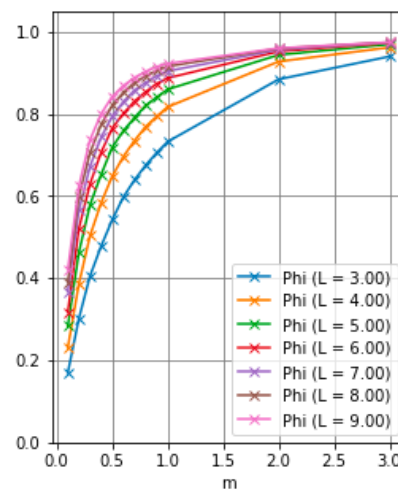


Figure 9 The energy efficiency (ϕ) as a function of number of platooning-equipped vehicles (m) for the planned decision function with $l_p = 2$ with different plan lengths (L).

We also performed simulation for larger values of l_p , which did not show significant effects on either the energy or the transport efficiency. So the simulations indicate that requiring longer joint platooning time does not change the transport and energy efficiency as a function of platooning penetration significantly.

As described in Chapter 4, the fuel savings is different for different positions in the platoon. We thus extended the simulation model to study different ways of determining

who should be the leader of a platoon. We used both a point-based system and a money-based system. In the point-based system, trucks are given points based on their benefit from platooning. When a platoon is formed, the truck with the largest aggregated benefit from platooning (*i.e.*, the largest number of points) is selected as leader. In addition to measuring the transport and energy efficiency, we also measured the real fuel consumption and average platoon size. Interestingly, the results do not depend sensitively on which model is used for determining leader of a platoon.

Further results on simulations of the opportunistic platooning and $l_p = 1$ model can be found in (Axelsson, 2018), while results for $l_p > 1$ and different ways of choosing the leader will be published later.

5.1.4 Conclusions

The simulations show the benefits of a coordination mechanism, both in order to communicate information necessary to form platoon and to distribute the benefits equally between all participants. Choosing platoon leader based on points or money gives a more equal distribution of utility, but the measured transport and energy efficiency do not depend on this.

In general, we can say the following things about the dependence of energy and transport efficiency and waiting time on platooning properties:

- The energy efficiency increases with the number of vehicles.
- The energy efficiency increases with the length L of the planning horizon.
- The transport efficiency increases with the number of vehicles.
- The transport efficiency increases with the length L of the planning horizon.
- The average waiting time decreases with the number of vehicles.
- The average waiting time increases with the length L of the planning horizon.

It should be noted in the analysis above the factor m is decisive for how much platooning will be achieved. The value $m = 1$ corresponds to the baseline of the current density of trucks on Swedish motorways, and thus shows a situation when all trucks in Sweden have been equipped for platooning. However, this situation takes many years to achieve and in the mean time, the penetration rate will be much lower and hence platooning opportunities will be rarer. During that phase, it is even more important to have access to planning and match making to be able to reach acceptable benefits.

Also, it is important that there is one ecosystem for platooning where all brands and haulers can platoon together. If the market is fragmented, this will also correspond to a smaller value on m , and hence quickly decreasing value.

We will return to the business aspects of the early phases of introduction and of the risk of fragmentation in Section 6, when discussing how match making services should be organized.

5.2 Formation at common origin of departure

In this section, we consider a hub-based platoon coordination problem in which vehicles arrive at a hub and wait in order to form platoons with other vehicles. In today's transportation infrastructure, there are many examples of locations which could function as hubs, *e.g.*, freight terminals, gas stations, parking areas, tolling stations, harbors, etc. The rest-time of drivers is strictly regulated and long distance drivers are required to rest during their journeys. Rest areas are ideal hub locations since the drivers can rest while waiting for other vehicles to platoon with. We develop models for the case where platoons form at a hub (called origin) and vehicles can platoon to a proceeding hub (called destination), as in Figure 10.

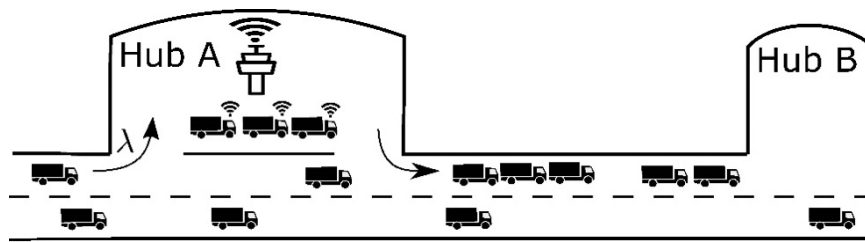


Figure 10 Platoon formation at a hub.

We assume that vehicles are owned by competing transportation companies and each vehicle is interested in optimizing its own transport cost which includes its profit from platooning and its cost of waiting at the hub. This leads to a game theoretic formulation of the platoon coordination problem where the strategies of the vehicles are their departure times from the hub. It is assumed that two vehicles will form a platoon if they depart from the hub at the same time.

First in this section, the model of the waiting cost and profit from platooning are presented. Second, three profit-sharing models are formulated and in connection to each model it is explained how the platoon leaders are assigned and how the departure times (and implicitly the platoon formations) are decided. Finally, the profit-sharing models are evaluated in a simulation of a hub-based platoon formation scenario.

5.2.1 Cost of waiting and profit from platooning

There is a cost associated with departing later than the default time, *e.g.*, due to increased driver cost and cost related to later arrival of goods as discussed in Section 4.3. If vehicle i departs at d_i its time-penalty is $B_i(d_i)$. We assume $B_i(d_i) \geq 0$, and $B_i(d_i^d) = 0$ if d_i^d is the default departure time of vehicle i .

The profit from platooning is vehicle-dependent and differs for a platoon leader and its followers. The profit of vehicle i is R_i^l when it is a platoon leader between the origin and destination. The profit of vehicle i is R_i^f when it is a follower between the origin and destination. Profit-sharing is needed within platoons in order for competing transportation companies to collaborate in forming platoons due to the unbalance in profit. In the next section, three of the profit-sharing models discussed in Section 4.2 above are formulated as utility functions of vehicles.

5.2.2 Profit-sharing models, leader assignment and decision-making of vehicles

Three profit-sharing models are formulated as utility functions of vehicles. Connected to each profit-sharing model, a leader assignment approach is proposed and it is explained how vehicles decide their departure times. For an extensive description of the profit-sharing models and the decision-making models, we refer to the work in (Johansson & Mårtensson, 2019) and (Johansson, Nekouei, Johansson, & Mårtensson, 2018).

5.2.2.1 Profit-Sharing Model 1: Even out

The leader of a platoon receives a monetary compensation from its followers, according to a standardized agreement, to even out unbalance in the profit between the leader and its followers and the leader is assigned randomly. This model corresponds to the Split-to-Leader model of Chapter 4. Vehicles do not reveal the actual individual profit from platooning; this might be information that they want to keep secret. However, they have agreed on standard values of the profit between the origin and the destination. The standard values of the profit for being a leader and follower are denoted by R^l and R^f , respectively. In a platoon of $n > 0$ vehicles, the transaction from each follower to the leader is $(R^f - R^l)/n$. If vehicle i is a leader in a platoon of n vehicles and its cost of waiting is $B_i(d_i)$, then its utility is:

$$u_i = R_i^l + \frac{n-1}{n}(R^f - R^l) - B_i(d_i),$$

where the first term is the platooning profit, the second term is the received transactions from its followers and the third term is the waiting cost. If vehicle i is a leader in a platoon of n vehicles, its utility is:

$$u_i = R_i^f - \frac{1}{n}(R^f - R^l) - B_i(d_i),$$

where the first term is the platooning profit and the second term is the transaction to the leader. Note that the utility for being a follower and leader are equal when the platooning profit coincides with the standardized platooning profit, *i.e.*, when $R^f = R_i^f$ and $R^l = R_i^l$.

The leaders in each platoon are assigned by randomization and the vehicles update their departure times, one by one, given the other vehicles' departure times, until no vehicle can increase its utility. The converging set of departure times is a so-called Nash equilibrium and we consider it as the solution concept of the platoon coordination problem.

5.2.2.2 Profit-Sharing Model 2: Score system

The profit from platooning is balanced over time by a score system where in each platoon formation the vehicle with the lowest score is assigned to be the platoon leader. The score of a vehicle decreases when it is the platoon follower and increases when it is the platoon leader. In this way, the leaders at the current platoon formation instance are less likely to be leaders at the next platoon formation instance. Let $\Delta s_i^l(n)$ and $\Delta s_i^f(n)$ denote vehicle i 's score update if it is a leader and follower in a platoon of n vehicles, respectively.

Vehicle i values each score unit as β_i . If vehicle i is a member of a platoon of n vehicles and it becomes the leader according to the score system, then its utility is:

$$u_i = R_i^l + \beta_i \Delta s_i^l(n) - B_i(d_i)$$

and if it becomes a follower its utility is:

$$u_i = R_i^f - \beta_i \Delta s_i^f(n) - B_i(d_i).$$

The leaders are assigned by the score system and the vehicles update their departure times to maximize their utility functions, one by one, until the algorithm converges to a Nash equilibrium.

5.2.2.3 Profit-Sharing Model 3: Market

A sub-set of the vehicles are sellers and the rest of the vehicles are buyers. Each seller offers the buyers to be platoon followers for a price that the seller decides. The buyers decide which seller to follow. Then, each seller seeks the price that maximizes its own profit which is a combination of its profit for being a leader and the payment it receives from the followers. The buyers decide to follow the most profitable seller in terms of price and waiting cost. The utility of seller i is:

$$u_i = R_i^l + (n - 1)p_i$$

if its price is p_i and it has $n - 1$ followers. If buyer j follow seller i , its utility is:

$$u_i = R_i^f - p_i - B_i(d_i).$$

Each buyer follows the seller that maximizes its utility and each seller maximizes its utility function with respect to its price and given the other sellers' prices. The sellers depart at their default departure times and update their prices, one by one, until the algorithm converges to a Nash equilibrium (in prices). If a seller does not receive any followers, it is converted into a follower, and the procedure is repeated until all sellers have at least one follower.

5.2.3 Numerical comparison of the profit-sharing models

In this section, the profit-sharing models are evaluated in a simulation of a hub-based platoon formation scenario. First, the setup of the simulation is presented. Second, the evaluation of the profit-sharing models is presented.

5.2.3.1 Setup of simulation

We consider the hub-to-hub based platoon formation scenario in Figure 10. We assume the platooning profit to be 105 SEK of the followers and 0 of the leaders. This corresponds to a case where the only benefit from platooning is the fuel saving, the distance between hubs is 200 km, the fuel consumption of vehicles are 0.35 l/km, the followers save 10 % fuel by platooning and the fuel price is 15 SEK/l (values used are inspired by and compatible with those presented in Chapters 3 and 4). The default departure times of vehicles are randomized in a window of 30 minute and the maximal waiting time of the vehicles is 10 minutes. The time is discretized with time-step length 1 minute. The cost

of waiting 1 minute is 10 SEK. The results presented below are averaged over 50 Monte Carlo samples.

5.2.3.2 Evaluation of profit-sharing models

The three methods of calculating departure times which are connected to the three profit-sharing models as explained in the previous section, are compared with two additional cases: (1) Vehicles are cooperative and select their departure time to maximize the overall profit at the hub, and (2) vehicles depart at their default departure times and vehicles platoon spontaneously if they share default departure time.

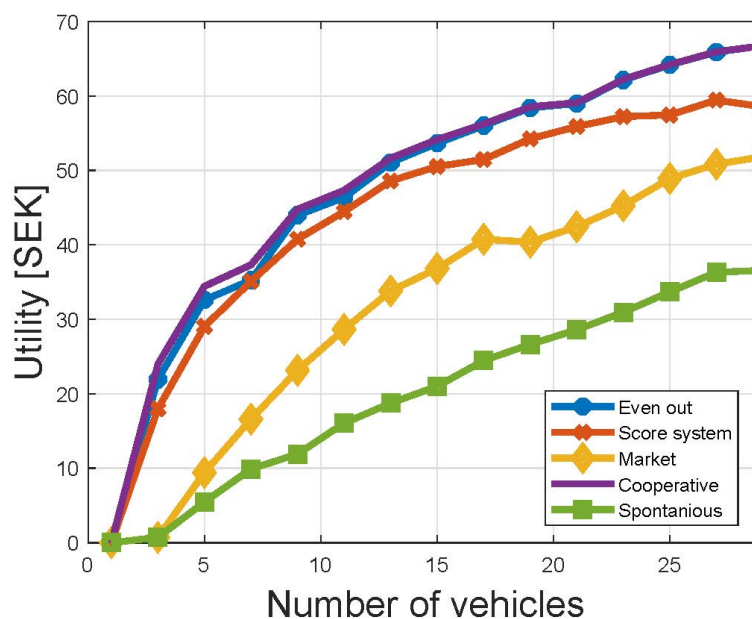


Figure 11 Average utility as a function of number of vehicles at the hub.

The average individual utility of the distribution models is shown in Figure 11. The highest individual utility is obtained when the vehicles are cooperative. This is expected since the vehicles aim to maximize the total utility of all vehicles. Close to the utility of cooperative model is the utility of the model called even out while the utility of the model called score system was lower. This can be explained by the fact that vehicles with low scores have low incentives to deviate from their default departure time and platooning opportunities are not exploited. The utility of the model called market is low in comparison to the utility of the other models. This is explained by the fact that buyers tend to spread out on sellers even when their default departure times are close which obtains lower total utility than if they depart in the same platoon. The spontaneous solution obtained lowest utility, as expected.

The average percentage of followers is shown in Figure 12. We see that when the number of vehicles is greater than 8, the percentage of followers is higher in the solutions of score system than in cooperate and even out solutions, even though the average utility is higher for cooperative and even out. This is possible because a higher percentage of platoon followers can imply fewer platoons but longer platoons which can lead to higher waiting cost of vehicles and therefore lower utility.

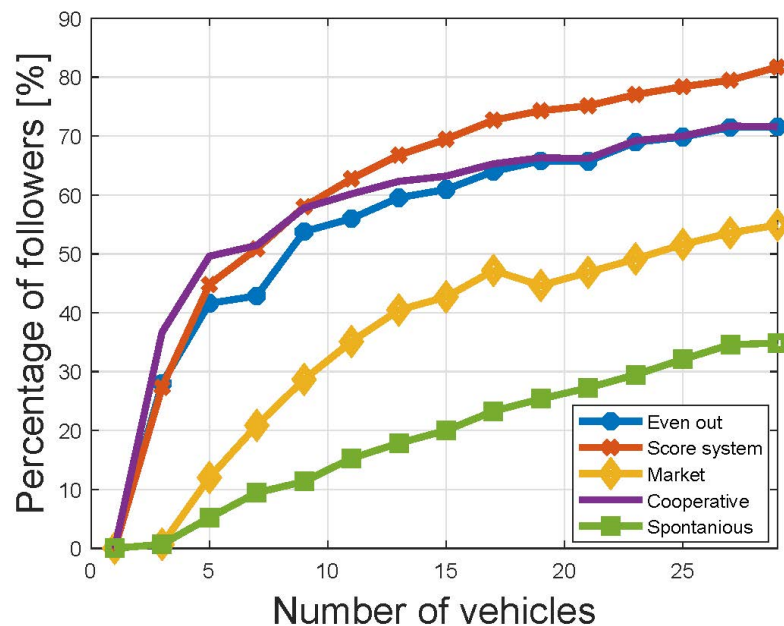


Figure 12 Average percentage of followers as a function of number of vehicles at the hub.

5.3 Conclusions on platoon formation

The conclusions on platoon forming are mostly intuitive. There is a clear need for sharing of information to facilitate platoon formation in order to achieve good energy efficiency. The exact method by which platoon leader is selected and how the benefits are distributed do not have a large effect on the efficiency. When it comes to formation at hubs, the even out model is significantly better than the other tested models for sharing of benefit whereas the score system will lead to longer platoons.

6 Mediating services

Main author of this chapter: Jakob Axelsson

In order for truck platooning to be viable, it is necessary to have a mechanism that enables trucks to be made aware of platooning opportunities. In Chapter 5, we saw how platoons could be formed either dynamically on road or at hubs. In both cases, there is a need for trucks to be made aware of possible platooning opportunities. As described in Chapter 4, waiting for a platoon to form is associated with costs, and the fuel consumption reduction is different depending on the position in the platoon. For haulers to be willing to participate in platooning, it is thus necessary to share costs and benefits.

For all these reasons, it is necessary to have *mediating services* that help provide information and broker platooning possibilities. The need for a platoon to include trucks belonging to different haulers and from different manufacturers further accentuates the need for mediating services.

One such mediating service is for match-making, that helps trucks equipped for platooning to find others to join (especially important for multi-brand platooning). If such a service is not included, there will be difficulties in forming platoons, in particular in situations with few platooning prepared trucks in the same region, such as will be the case during the early introduction of the concept.

Another mediating service is for allocating the profits from platooning, and this is needed since the gains are unevenly distributed among the participants. Although the leader of the platoon also gets somewhat lower fuel consumption, the followers have much more benefit. Also, during formation some vehicles must wait for others and will thus arrive later at their destination and have a lower utilization, which can be seen as a cost. In some cases, overall societal costs and benefits (*e.g.*, reduction of CO₂ exhausts) should also be taken into account, which also is facilitated by having a mediating service.

In this chapter, we evaluate different ways of providing these mediating services, based on the work presented in (Axelsson, 2019). The main evaluation criteria when comparing different answers to these questions is what the overall effects will be on the platooning purpose, which is to reduce fuel consumption. When discussing and analyzing the mediating services, it will be useful to think of the platooning trucks as parts of a *system of systems* (SoS). An SoS is a set of independent *component systems* that can choose to collaborate in order to gain benefits. In the case of platooning, each individual truck that is equipped for platooning is a component system. A group of trucks that form a platoon is called a *constellation* in SoS terminology.

6.1 Relevant actors

The research method applied here is a qualitative system dynamics analysis, since platooning has not yet been deployed in practice (with a few exceptions (Switkes, Boyd, & Stanek, 2014)) and hence little or no empirical data on large scale effects is available. The findings have been validated through reviews by representatives of the different roles in a truck platooning ecosystem.

In the present truck-based transportation ecosystem, there are four different kinds of actors present who have dedicated roles today:

- *Haulers*. The companies that have the role to provide transportation services by operating fleets of trucks.
- *Truck Original Equipment Manufacturers (OEMs)*. The companies whose role it is to produce trucks and deliver them to the haulers.
- *Infrastructure providers*. Public authorities or companies that have the role to operate the road and telecom infrastructure necessary for the haulers.
- *Third-party service providers*. Companies that have a role to assist haulers to make their operations more efficient.

Each of these actors is a candidate for taking on the additional roles needed in the platooning SoS, which are to operate mediating services for fuel savings sharing and match making.

6.2 Life-cycle perspective

The basis for the analysis is the requirement that all actors in the SoS gain more than their costs over time. This constraint can be expressed more precisely by stating that all actors must have a positive net present value (NPV), where:

$$\text{NPV} = \sum_{t=0} \frac{R_t}{(1+i)^t}$$

Here, t is time; R_t is the net value flow over the time period (*i.e.*, income – cost); and i is the discount rate (*i.e.*, the return that can be earned on alternative investments with similar risk). Using NPV for the analysis makes it possible to consider both short term and long-term value flows in a reasonable way. The need to do so becomes apparent when the evolutionary stages of this SoS are identified:

1. *Establishment (E)*. Actors make initial investments required to provide the basic products/services. No value can be created before this stage is completed, and hence there are no incomes.
2. *Growth (G)*. Products/services are available, and an increasing number of users start joining the SoS. There are investments to enhance capacity.
3. *Steady state (S)*. Usage growth has reached a plateau. There are investments in maintaining equipment, and in rationalizing operations to reduce costs.

A viable ecosystem must provide a positive net present value for all involved actors, and the initial investments must eventually pay off, otherwise the actor has no incentives to join the SoS.

6.3 Cost-benefit analysis

In order to determine the NPV, we must systematically assess what the consequences are if any of the present types of actors take on the new roles to provide match-making and fuel savings sharing.

Table 23 Value flows between roles and potential associated costs of value creation.

Role		Value	Potential provider costs per evolutionary stage	
<i>Provider</i>	<i>Beneficiary</i>		<i>Fixed</i>	<i>Variable</i>
Transport service user	Society at large	Economic growth	None	None
Hauler	Transportation service user	Reduced transportation cost	Investments in trucks prepared for platooning [G, S]	Service fees for match-making, fuel savings sharing, infrastructure [G, S]
	Society at large	Reduced environmental footprint		
Truck OEM	Hauler	Trucks prepared for platooning	Investments in engineering, production equipment [E]	Purchased parts, assembly staff, equipment maintenance [G, S]
Fuel savings sharing service provider	Hauler	Predictable cost reduction for all platooning participants	Investments in service engineering, IT equipment [E, G]	Equipment maintenance, service fees for communication [G, S]
Match-making service provider		Cost reduction by increasing platooning rate		
Infrastructure provider	Hauler	Road & communication infrastructure prepared for platooning	Investments in road infrastructure, IT and telecom equipment [E, G]	Infrastructure maintenance and operation [G, S]
	Fuel savings sharing service provider	Communication infrastructure prepared for platooning		
	Match-making service provider			

In Table 23 we show the results of an analysis of values created and costs incurred by different stakeholders in the different evolutionary stages of platooning.

A viable business model requires that all actors have a positive net present value, and this means that after the roles are distributed to actors, all the costs have to be covered. It is thus necessary to find and evaluate potential payment streams.

A few things are worth noting about payment streams:

- Just like costs, payment streams can be fixed or variable. For instance, it is possible to buy a truck (a fixed cost) or pay for a service on a per-use basis (a variable cost).
- A role that receives a value is more likely to be willing to pay for that value, and hence the most likely candidates for payment streams are the reverse of the value streams shown in Table 23.
- Eventually, all payments need to come from the beneficiaries of the SoS, i.e., in the platooning case the transport service users and society at large.
- A payment from one role must be matched with an income of another role, to ensure a consistent analysis and a closed system model.

The payment streams identified are presented alongside the costs for each role in Table 24.

Table 24 The costs and benefits of different ways of handling the mediating service.

Role	Potential costs		Potential incomes	
	<i>Fixed</i>	<i>Variable</i>	<i>Fixed</i>	<i>Variable</i>
Transport service user	None	None	None	Reduced transportation service fee [G, S]
Hauler	Investments in trucks prepared for platooning [G, S]	Service fees for match-making, fuel savings sharing, infrastructure [G, S]	Subsidies for buying platooning equipped trucks [G, S]	Transportation service fee [G, S]
		General tax on transportation, fuel, vehicles [E, G, S]		Subsidies for using platooning trucks [G, S]
				Reduced fuel consumption [G, S]
Truck OEM	Investments in engineering, production equipment [E]	Purchased parts, assembly staff, equipment maintenance [G, S]	Subsidies for developing platooning equipped trucks [E]	Truck purchase [G, S]
	Mediating service entry fee [E]			Service fee for platooning usage [G, S]
Fuel savings sharing service provider	Investments in service engineering, IT equipment [E, G]	Equipment maintenance, service fees for communication [G, S]	Service entry fee [E]	Service fees [G, S]
Match-making service provider			Subsidies for developing or operating service [E, G, S]	
Infrastructure provider	Investments in road infrastructure, IT and telecom equipment [E, G]	Infrastructure maintenance and operation [G, S]	Service entry fee [E]	Service fees [G, S]
			Subsidies for developing or operating service [E, G, S]	
Society at large	None	Subsidies for developing, buying, or using platooning equipped trucks [E, G, S]	None	General tax on transportation, fuel, vehicles; VAT [E, G, S]
		Subsidies for developing and operating mediating services [E, G, S]		

It should be emphasized that the payment streams are potential, and there is thus a choice to make which ones of these should actually be implemented as part of the business model. This will be discussed further below. To ensure that no possible options were left out, the payment streams considered cover a broad range. Since all incomes to a role must be matched with a cost for another role, this leads to additions of some possible costs that were not present in Table 24, which focused only on the inherent costs of value creation.

These added costs include entry fees for the mediating services, meaning that a truck OEM may need to pay a licensing fee to be able to prepare its products for using that service. They also include costs, and incomes, related to the potential role that public authorities can play to stimulate the development of a platooning SoS with the benefit of reduced environmental effects. This includes subsidies, which can reduce the entry threshold for companies to develop and use platooning, and also taxes, both for funding subsidies and also for creating incentives for beneficial behavior on the market (*e.g.*, a tax on fuel would stimulate reduction of fuel consumption, and hence encourage platooning).

Some of the incomes are in fact reduced costs compared to the current situation. In particular, reduced fuel consumption due to platooning will lower the cost for the haulers, which in turn may lead to reduced costs for the transport service users.

In the evaluation of costs and incomes, summarized in Table 24, it can be seen that the two mediating services for fuel savings sharing and match-making have identical characteristics. In principle, they can still be separated, but there are some clear benefits in keeping them together:

- It is easier from a user's perspective to only connect to one service, since only one business relation is needed.
- There are economies of scale, where most of the IT infrastructure is similar and can be reused and some of the development costs can be shared.
- It becomes less important that each of the services carries its own cost, but it is enough that they together have a positive balance.

Due to these benefits, we recommend that the services are packaged together.

6.4 Service provider

It remains to analyze who should provide the mediating services. It could be provided by haulers, OEMs, third parties, or infrastructure providers:

- *Haulers:* The hauler market is very distributed, with a large number of companies active even within a single country. Some of them are large, and already utilize advanced fleet management systems to plan and execute their operations. However, having one mediating service per hauler would fragment the market, and reduce the possibilities to let trucks from different haulers platoon together. Therefore, a federated solution would be needed, and this is equivalent to having a third party service provider funded by both an initial entry fee for investments in creating the services, and a running service fee for operation.
- *Truck OEMs:* If the services were connected to a particular truck brand, the same interoperability problem would occur as if the services were operated by the haulers, but on a much smaller scale. This is due to the fact that the global truck market is controlled by less than ten major brands. It would thus be easier to let them agree on a federated service that sets a global standard, not the least since they already need to agree on technical standards for short-range communication between the trucks. It is again equivalent to having a third party operator, except that the OEMs would jointly pay investments through an entry fee. However, the

payment stream from the haulers would now go through the OEM, and this opens possibilities for the OEM to use part of that service fee to balance other costs.

- *Third party service provider*: The mediating services may be operated by a third party, as a separate organization. As explained above, the haulers or the truck OEMs could jointly create that organization, but it could also be an independent company. The benefit of this is that a centralized solution can be found, but there is also a risk that competing services are founded leading to a situation where platooning with trucks connected to different service providers will be difficult. If the service is not backed by OEMs or haulers, the provider has to make the initial investments during establishment themselves, which has a considerable risk that there will not be sufficiently many trucks joining the service to cover those costs.
- *Infrastructure providers*: The final option is to have infrastructure providers expand into mediating services, and it seems most likely that the road administrations would then take this role. Since these are public services in most countries, the services could be funded by taxes, road tolls, or similar. However, there is a large risk that the services would be per country, which would make it difficult for the fairly common cross-border long-haul transportation.

The objective of the platooning SoS is to maximize overall fuel savings, since this creates both an economical room for the necessary investments and also benefits the environment and thus society at large. The fuel savings is proportional to the platooning rate. This enables us to give the following guidelines for determining who should operate the mediating services:

1. *Maximize number of prepared trucks*: It should be as attractive as possible for haulers to invest in platooning equipped trucks, and hence the cost difference should be minimal. Here, the optimal solution is to have the equipment installed on all trucks, *i.e.*, no cost difference.
2. *Minimize number of service providers*: If there is a fragmentation, where only some trucks can platoon with each other, there will automatically be a reduction of the platooning rate as a consequence of Metcalfe's law or its variants (Briscoe, Odlyzko, & Tilly, 2006). The optimal solution here is to have one global service provider.
3. *Maximize incentives for platoon formation*: A system that can distribute costs and benefits among platoon participants can improve these incentives considerably, but it is also necessary to keep all service costs low, such as a running cost for connecting to a platoon through the mediating services, if such a cost is considered.

6.5 Recommendations

Based on the analysis, we arrive at the following recommended business set-up to maximize platooning rate:

- The OEMs should jointly set up a service provider for match-making and fuel savings sharing, since this is the fewest number of actors that can create a single global service solution.

- The OEMs should have platooning equipment as a standard offer on their trucks, since this will guarantee the shortest possible transition through the evolution phase.
- If a money-based sharing system is used, the OEMs could charge haulers based on a per km usage fee, which is invoked whenever a truck joins a platoon. This can be combined with the fuel saving sharing, and possibly also for sharing waiting costs, so that the net fee is sometimes negative (e.g. for a platoon leader) and sometimes higher (e.g. for a follower). The fee should in any case be much smaller than what the hauler gains from joining the platoon.
- There is no need to introduce an extra business relation for the hauler, which instead extends the already existing relationship with the OEM⁵. In this way, communication with mediating services can be handled through the on-board equipment and an OEM server, with no needs for third parties to interface to the physical trucks. The OEMs can distribute payments between them on behalf of their users, if there is a multi-brand constellation.

The recommendations are viable in the sense that all actors will have a chance to get a positive NPV, although the exact calculation requires more quantitative data than we have available today. They reach the optimum solution on the first two criteria mentioned in Section 6.3 above, but not on the third since there is a running fee for connecting to a constellation. However, this running fee will only be charged in situations where the haulers have an income and is thus risk free to them.

The solution also has the benefit that the OEMs have a very strong incentive to create effective services for match-making, since it will directly affect their incomes, and this will have a positive effect on overall savings.

In this set-up, society at large is a free-rider, with no involvement. However, it can optionally be added a government intervention through taxes and incentives. For instance, an extra tax on fuel would give a steady income and create further incentives for reducing consumption, and the income could be used to give subsidies to development of technologies such as platooning to reach those reductions.

⁵ Of course, the hauler also has business relations with, *e.g.*, the logistics service providers who in principle could also take on the mediator role.

7 Conclusions

In this chapter, we return to the list of high-level research questions from Chapter 1 and list the results pertaining to each of them. We also describe some future research needs related to the work presented in this report.

The analysis presented in this report is based on a Swedish context. Hence some caution must be exercised when extrapolating the results to other markets – if the underlying conditions and transport patterns are different, then the results could be different. For instance, the fuel consumption part is valid for European conditions, but not valid for those parts of the world where speed limits for heavy trucks are higher than in Europe (*e.g.*, the US).

7.1 Cost and benefit for businesses

What are the costs and benefits of platooning? How big are the fuel reductions? What is the cost of waiting to form a platoon? What is the cost of re-ordering a platoon?

Section 3.1 analyzed the potential savings in fuel from a societal and business perspective. The combined benefit for businesses of platooning is up to 600 million SEK for motorways with 110 km/h and 120 km/h speed limits, while the proposed second step 2+1 median barrier roads would give an additional 500 million SEK in benefits. Note that large parts (50% for 110 km/h and 120 km/h, 35% for 2+1 median barrier roads) of these savings do not come from the platooning *per se*, but rather from reducing speeds. To realize the full potential, it is thus important to include measures to ensure that leaders do not break the speed limit (*e.g.*, more advanced speed regulators).

Driver-time savings were shown in Section 3.2 to reach up to 2 billion SEK, if followers were fully autonomous or drivers allowed to perform other tasks when platooning.

It is also important to consider the costs and benefits for an individual business. In Section 4.1, different assumptions on fuel savings were listed. Since detailed information about fuel consumption is treated as restricted information, the assumptions in Table 6 and Figure 3 provide good numbers to be used as a reference also for future work.

In Section 4.3 we studied the cost of forming a platoon. The results could be used for further simulations or analytical studies of platooning. The most important results are given in Table 13, Table 17, Figure 6, Table 18, and Table 20. Section 4.3.4 gives the following guidelines:

- Waiting a few minutes in order to enable a couple of hundred kilometers of platooning is reasonable.
- Waiting for another truck a few kilometers behind in order to afterwards being able to do a couple of hundred kilometers of platooning also seems reasonable, at least for the involved trucks.
- Finding an alternative route, which is only a few kilometers longer, and that way being able to do some platooning, does not seem like something that will happen often.

The issue of reordering trucks in a platoon and its associated costs was described in Section 4.4, with the main conclusion that the cost for a reordering action is very small for the involved trucks. So for instance a system or a driving culture where the trucks take turns in leading, like bicycle racers do, could be a possibility. The reordering occasions would not have to cost too much.

There are also costs and benefits for society of platooning, the results on this are summarized in Section 7.4.

7.2 Payments

Is there a need for payments between trucks to share the benefits and costs of platooning? If so, how should the payments be organized?

Section 4.2 dealt with the important issue of sharing of the fuel savings. A conclusion from discussions with haulers is that fuel savings sharing is indeed necessary for platooning to be successful. This section also provides us with recommendations on what sharing model to use and how to compute the fuel savings:

- For balancing of fuel savings between platooning participants, start with a points system. The points system as described in Section 4.2.4.1 is a starting point. The followers pay $2/N$ points per kilometer to the leader. When forming a new platoon, the truck with the lowest score takes the lead.
- If a points system is found to be insufficient or not fair enough, then consider one or both of the following:
 - Real money transactions instead of only points. Use the Split-to-Leader (SNL) model as distribution model.
 - A model for quantifying savings. Use a commonly accepted standard model instead of attempting to estimate actual savings. The model described in Section 4.2.3.2 is a starting point.

The discussion on how to organize payments also relates to mediating services, which is discussed in the next subsection.

7.3 Coordination

How should a platoon be coordinated? How should they form, operate, and dissolve? In what order should the vehicles in a platoon drive? Should the vehicles re-arrange themselves in order to spread the fuel reduction benefit more equally? This report deals with the business aspects of these issues, while the technical aspects are addressed elsewhere.

As described in Section 3.5, the gradual roll-out of platooning technology as well as the diverse list of truck manufacturers will inevitably lead to the presence of different levels of platooning technology in the truck fleet. This leads to the following recommendations:

- Ensure that each level of platooning is backwards compatible with previous levels.
- It is unnecessary to allow different levels of platooning within the same platoon.

The different costs and benefits associated with platoon formation relate to the research questions on coordination, and the results were summarized in Section 7.1.

From Chapter 5 on platoon formation, the main results are:

- Communication to share of knowledge is needed in order to gain energy efficiency.
- The exact method used to share benefits does not matter so much for energy efficiency.
- The even out model is better than the others for utility sharing.

While the need for mediating services was established in Section 5, the results of the analysis of how to implement this mediating service presented in Section 6 are:

- The OEMs should jointly set up a service provider for match-making and fuel savings sharing, since this is the fewest number of actors that can create a single global service solution.
- The OEMs should have platooning equipment as a standard offer on their trucks, since this will guarantee the shortest possible transition through the evolution phases.
- The OEMs should charge haulers based on a per km usage fee, which is invoked whenever a truck joins a platoon. This can be combined with the fuel saving sharing, and possibly also for sharing waiting costs, so that the net fee is sometimes negative (*e.g.*, for a platoon leader) and sometimes higher (*e.g.*, for a follower). The fee should in any case be much smaller than what the hauler gains from joining the platoon.
- The hauler only has a business relation to the OEM where it bought the truck, and hence just extends an already existing relationship. In this way, communication with mediating services can be handled through the on-board equipment and an OEM server, with no needs for third parties to interface to the physical trucks. The OEMs can distribute payments between them on behalf of their users, if there is a multi-brand constellation.

7.4 Societal perspective

What are the consequences and potential for the society and other road users and how can their acceptance of platooning be assured?

Chapter 3 shows that there is a significant potential for fuel savings with platooning, up to 25 million litres per year worth on the order of several hundred million SEK for society and businesses (Section 3.1); this also entails a vast possible savings of CO₂ exhausts, up to 50 million kg CO₂. This societal benefit will increase further with the new model for valuating CO₂ exhaust mentioned in Section 3.1, when the societal value of the CO₂ reductions will be 700 million SEK, bringing the combined socio-economic value of fuel and CO₂ exhaust reductions to 1 billion SEK. For the second step of 2+1 median barrier roads, the socio-economic value of the savings in fuel and CO₂ exhausts are 800 million SEK. As noted in Section 7.1, large parts of these savings come from the reduced speed

rather than from platooning, necessitating a system for inducing the leaders to follow speed regulations to fulfil the potential.

In addition, should platooning be implemented with fully autonomous trucks or drivers allowed to perform other tasks when platooning, there is a very large potential reduction of driver time (Section 3.2), with market value of around 2 billion SEK.

Effects on safety and level-of-service are harder to quantify, but there are indications that platooning could lead to increased safety (Section 3.3). Important issues are the design and frequency of reorders as well as warning devices on platoons.

7.5 Future research needs

Many of the results presented in this report naturally give rise to follow-up research questions.

7.5.1 Platooning as driver support or assisted driving

As seen above, large parts of the potential fuel savings and exhaust reductions seem to come from the reduction in average speed rather than from the platooning as such. To realize these potentials it is thus important to ensure that platoon leaders follow the speed regulations. This could be achieved by developing more advanced speed regulators and including speed limitations in software. While the technology to achieve this exists today, more research is needed on possible safety consequences of this as well as on the interaction between humans (drivers as well as other road users) and the autonomous systems. How to ensure that such measures are accepted by drivers, haulers and other road users also needs to be investigated.

7.5.2 Refined analyses

There are issues relating to multi-brand platooning which we have not been able to study. A partial list of future research needs within the area is:

- There is a need for further user studies and analysis of data to confirm the need for sharing of fuel savings.
- The model for fuel saving in Section 4.2.3.2 should be compared to empirical data
- The Split-to-Leader model for distributing fuel savings needs to be tested.
- Test the suggestions for estimating fuel savings proposed in Section 4.2.
- Further investigations of the effect of different ways of forming and maintaining a platoon on transport and energy efficiency are needed.
- The effect of platooning on society needs to be estimated more, and in particular the effect on the societal benefits of different types of mediating services needs to be studied.
- Viable business models for the mediating services need to be defined and tested.
- The resilience and robustness of the mediating services needs to be studied.
- The effects on the levels of service for other vehicles needs to be further investigated. The lack of empirical data on this necessitates the use of simulation models as in Section 5.1 for this.
- More research is needed on the safety aspects of platooning.
- There is a need for more studies on the effects on other road-users of platooning.

- Extending the analysis of reorderings to take account also of external costs, and to quantify the effects on safety and level of service.
- Extending the analysis of platoon formation costs to take account also of societal costs and benefits.

7.5.3 Autonomous vehicles

Throughout this report and the S4P project, we have assumed that all trucks in the platoon have drivers. If all followers of the platoon were autonomous trucks, the benefits of platooning would increase significantly. Much of the analysis done in the S4P project would have to be re-done for this case.

If autonomous vehicles are introduced in platooning, it is necessary to determine who is responsible for traffic violations initiated by the autonomous system.

Research is needed on the role of humans in autonomous vehicles used for platooning. When can a driver rest or perform other tasks instead of monitoring the driving? When is it possible to remove the driver completely? If all the trucks are completely autonomous, is there then a need for having remote drivers stand by to possibly take over control in difficult situations?

Using more autonomous systems in the vehicles would enable the vehicles to automatically adjust speeds and gaps according to the traffic situation. More research is needed on when and how this should be applied, and on the possible consequences for safety.

7.5.4 Electric vehicles

In S4P it was assumed that the trucks were driven by diesel engines. More research and testing should be done for when platooning is applied to long haul trucks with different propulsion systems, such as HEV (“mild” or with larger energy storage), Plug-In HEV, BHEV, fuel cell systems. Different powertrains will have very different costs for energy and for instance battery degradation, and this will affect the cost-benefit calculations for different platooning alternatives.

7.5.5 Field data and traffic environment

The benefits of platooning will depend substantially on the traffic environments where platooning is applied and also on how platooning is designed in traffic engineering terms. These two questions must be answered should any potential and effect assessment be possible.

The present method and system used by Swedish Transport Administration to estimate truck and truck combination mileages has a number of flaws. There are for this reason no official mileage estimates by road type and speed limit. This system would need some update efforts. Some areas where additional or better field data is needed are:

- Weights by axle combinations are only available in sample measurements from 2 motorway sites. It would be reasonably easy to increase this number to get more precise information.

- There is today no study on the present existence of truck platooning. It should be quite easy to do some sample measures.
- There is no survey today on the frequency and magnitude of motorway truck blockages in terms of safety and level-of-service.
- Truck and truck combination mileages by speed limit, road type and flow

7.5.6 Logistics aspects

Costs for changes in planning for the logistics service provider need to be investigated. Since most terminal to terminal departures are fixed in order to optimize the total logistics chain, we would need to consider changes in blue collar schedules and such.

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Appendix: Swedish traffic data

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In this appendix, we provide the background data used to derive the assumptions and conclusions described in Chapter 2.

A.1 Traffic count and weight in motion data

The Swedish Transport Administration carries out traffic count sample measurements (Forsman et al, 2014) over the whole Swedish state network. The count system divides the state network into some 33 000 count sections assumed to be reasonably constant from a traffic viewpoint. Some 22 000 are measured using sampling technique with intervals due to road category and some 11 000 are only assessed. The average traffic count section length is 4.5 km. Rural motorways are normally measured every 3 to 4 years but with a high degree of assessment. The reason for the large part assessments is work zone safety. An annual sample count consists of four measure periods; one per quarter with a maximum of 10 days data.

Gross and axle weights, length between first and last axle and headway (distance from front of vehicle to front of next vehicle) surveys are done in a limited, increasing number of spots (today 31) using WIM-technology (weight in motion) on bridges (Nationella Bärighetsgruppen, 2018). Headways are measured between trucks though not lane separated. There are two rural motorway sites. These are at Lödde on E6 in Skåne and on E4 at Mjölby in Östergötland. The sample size is one week annually.

In the estimation of vehicle mileages per year, passenger cars and trucks are only differentiated by axle distance (trucks defined as over 3.3 m). Motorway results with 110 and 120 km/h for 2010 to 2018 are given below.

Table 25 Lengths (km), mileages (Mapkm and Mvkm) and axle pairs/vehicle (ap/v) for motorways with 110 and 120 km/h from 2010 to 2018 (Trafikverket, 2019).

Year	Motorway 110				Motorway 120			
	km	Mapkm	Mvkm	ap/v	km	Mapkm	Mvkm	ap/v
2010	1301	10756	9562	1,12	341	2397	1961	1,22
2011	1288	10945	9736	1,12	342	2444	2000	1,22
2012	1308	10896	9707	1,12	342	2457	2013	1,22
2013	1279	10831	9471	1,14	341	2493	2042	1,22
2014	1302	10890	9492	1,15	341	2558	2096	1,22
2015	1307	11380	9880	1,15	341	2600	2124	1,22
2016	1308	11959	10295	1,16	341	2734	2240	1,22
2017	1312	12342	10591	1,17	341	2819	2307	1,22
2018	1312	12477	10720	1,16	336	2773	2272	1,22

ap= axle pair M=million v=vehicle

The 110 and 120 km motorway lengths are almost stable. Mileages increase some 1.8 to 1.9 % annually. The number of axle pairs per vehicle has increased over the years on 110 km/h motorways but not on 120 km/h. These estimates are not divided into rigid trucks

and articulated trucks (truck and trailers, incl semis) since the Swedish Transport Administration's pneumatic measurement technique cannot accurately differ between rigid and articulated trucks (Melen et al, 2014). 55-60% of the registered rigid trucks in the test were false and 2-3% of the rigid trucks were registered in other vehicle categories. Articulated trucks came out better from the test with 2-6% and 14-18% correspondingly. Table 25 shows the collected statistics for 110 and 120 km/h motorways.

The standard values for car, rigid truck and bus and truck combination shares and axle pairs per vehicle by road category given in Table 26 are often used (Trafikverket, 2016). Motorways 110 and 120 km/h are all on the European network proposing 6% rigid trucks (and buses) and 8% truck combinations.

Sample measurements from E4 and E6 for 2014 and 2015 in southern and middle Sweden give higher averages, 7% and 9% compared to 6% and 8% above. Both produce

Table 26 Vehicle types and average axle pairs by road category.

Road category	Cars		Rigid trucks + buses		Truck combinations	
	share	ap/veh	share	ap/veh	share	ap/veh
European	0.86	2	0.06	2.2	0.08	5.5
National and primary regional	0.92	2	0.04	2.2	0.04	5.5
Lower regional	0.95	2	0.025	2.2	0.025	5.5
Urban	0.93	2	0.04	2.2	0.03	5.5

a split with some 45% rigid trucks (and buses) and 55% truck combinations. The distribution of rigid truck and truck combination share of trucks by site is given in Table 27. Note that there is a much wider variation for truck and truck combinations than for rigid trucks.

Table 27 Rigid truck (and bus) and truck combination share distribution E4 and E16 by count station site.

Road category	Cars		Truck+bus		Truck+trailer	
	ratio	ap/v	ratio	ap/v	ratio	ap/v
European	0.86	2	0.06	2.2	0.08	5.5
National and primary regional	0.92	2	0.04	2.2	0.04	5.5
Lower regional	0.95	2	0.025	2.2	0.025	5.5
Urban	0.93	2	0.04	2.2	0.03	5.5

Ratios, gross weights and total axle length results for 2018 for E6 and E4 are listed in Table 28 by truck and bus type. Gross weights are quite stable between the two sites; some 12, 19, 30, 41 and 42 tonnes for rigid trucks, buses, Nordic and Euro combinations and trucks with two trailers.

Table 28 Ratios, gross weights and total axle lengths by truck type in 2018 WIM-data at WIM-stations E6 Lödde and E 4 Mjölby 2018.

	Lödde E6 180506-12				Mjölby E4 180409-15			
	share	truck + load		axle length	ratio	truck + load		axle length
	>3.5 ton*	mean	stdev	tot mean m	>3.5 ton*	mean	stdev	tot mean m
single truck	0,19	12,4	7,5	5,0	0,10	11,9	6,6	5,2
rigid bus	0,02	19,8	4,2	7,8	0,02	18,4	3,0	8,1
Nordic	0,59	31,4	10,9	12,3	0,47	29,2	10,0	12,5
Euro	0,18	40,0	15,9	19,2	0,35	42,0	13,9	20,3
truck multi	0,01	40,1	12,1	21,0	0,05	44,0	12,4	21,1
* gross weight								

The Nordic figure is close to the VETO assumptions with 40 tons for Nordic combinations.

Ratios vary due to transport types. E6 close to harbours with international traffic has a higher semi trailer ratio, 0.59 for E6 compared with 0.47 for E4, and a consequently lower truck and trailer ratio, 0.18 compared with 0.35 for E4. Both have high ratios of articulated trucks, 0.75 and 0.82. The rigid truck ratio is higher on E6, 0.19 compared with 0.10 for E4. The explanation is probably a more densely populated area with more delivery truck traffic at E6 in Skåne.

Annual average daily traffic volumes (AADT's) on motorways with 110 and 120 km/h have medians just below 20 000 vehicles per day and 85-percentiles up to 30 000 for 110 km/h with a few sites around and over 50 000 (perhaps errors in the data base). The latter are probably questionable from a safety viewpoint. The data is shown in Figure 13. A peak hour volume has on average a directional split around 60 to 40 and an AADT-percentage peak hour factor around 0.10 to 0.12. This results in median peak hours around $0.6 \times 0.11 \times 20\ 000 =$ some 1 300 vehicles per hour in max direction and in some extreme cases the double.

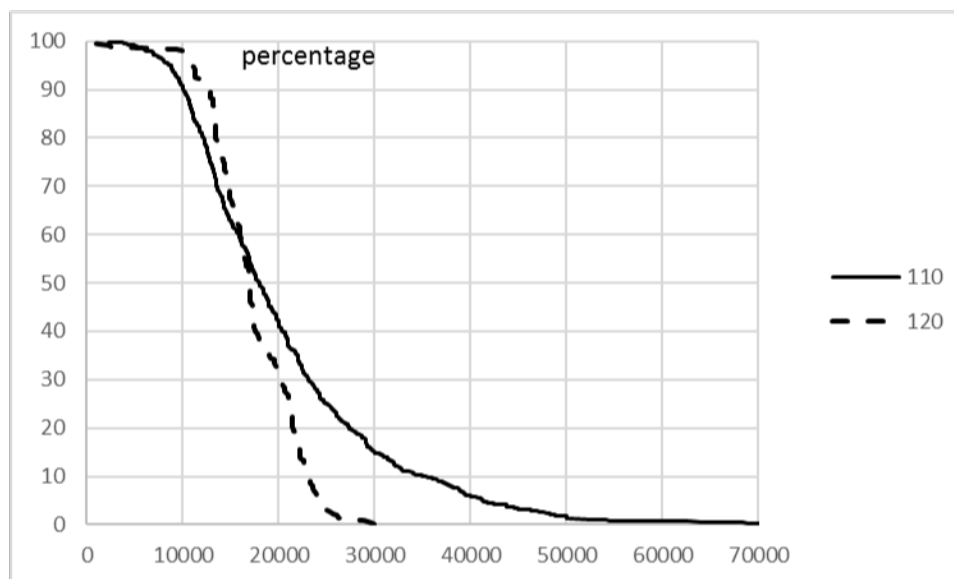


Figure 13 Two way motorway 110 and 120 km/h site AADT (annual average daily traffic) distribution.

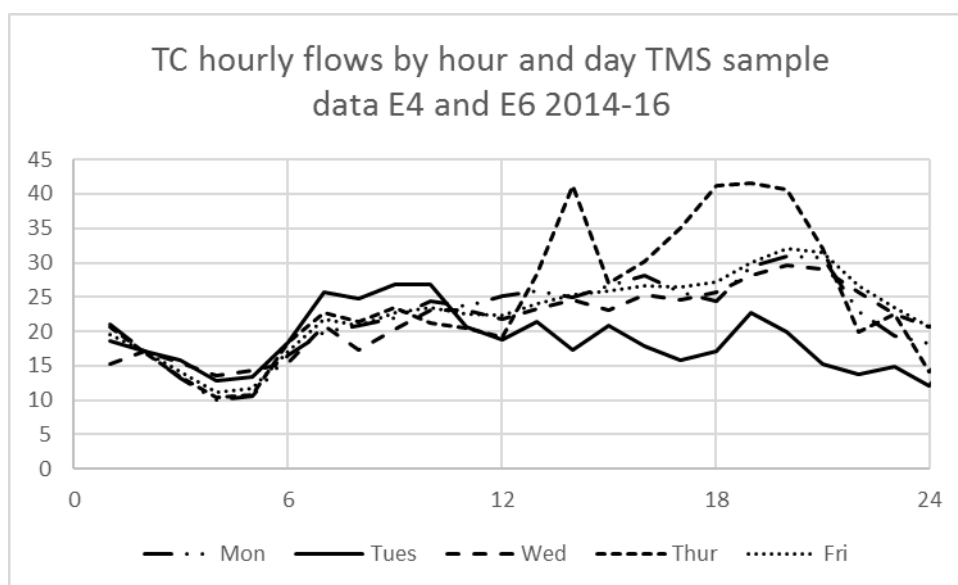


Figure 14 Two way motorway 110 and 120 km/h traffic count station data 2014-16 hourly truck combination flows by weekday.

Average hourly truck combination flows by weekday according to Swedish Transport Administration traffic count stations on E4 and E6 with speed limits 110 and 120 for the years 2014 to 2016 are shown in Figure 14. The hourly flows vary between a minimum around 10 early in the morning up to a rather stable value between 15 and 25 due to day with Thursday as an exception.

A.2 HBEFA and VTI analysis

Sweden with the Swedish Transport Administration as a partner uses HBEFA (Matzer et al, 2019) to report traffic emissions to EU (Naturvårdsverket, 2019). HBEFA requires data on mileages and weights for a number of road types/speed limits/road environment

and traffic situations. This mileage estimate is a joint effort between a number of Swedish organizations including the Swedish Transport Administration. It is hard for outsiders to find facts and assumptions on truck flows as they seem only to be found in data bases. They are based among others on vehicle inspection data.

The last update for motorway 110 and 120 km/h truck flows by traffic situation (free flow, saturated, heavy and stop and go) is shown in Table 29 proposing a total mileage 12117 Million vehicle km with out of these 1 294 trucks (HGV heavy goods vehicles).

The last published result (WSP, 2015) shown in Table 29 estimates 110 and 120 km/h motorways mileages in free flow conditions to be 0.128 x 76 176 million vehicle kilometres, *i.e.*, 9819 million vehicle kilometres in 2012. Mileages in higher flow conditions are only 0.15% compared with this 12.8%. The WSP data has been updated for 2018 (Yahya, 2019) see Table 29, giving a total mileage of 12.7 billion motor vehicle kilometres in free flow conditions; *i.e.*, with a 4.4% annual increase. Average gross weights are 17.6 tons for rigid trucks and 35 as an average for truck and (incl. semi) trailers.

Table 29 Motorway 110 and 120 km/h by traffic situation and environment mileages according to HBEFA 2018 update.

	Milage 2018 Million vehkm			
	Rural motorway		Urban motorway	
	tot	HGV	tot	HGV
110 free flow traffic	9819	1020	505	32
110 saturated traffic	49	5	3	0
110 heavy traffic	3	0	1	0
110 stop and go	1	0	0	0
110 tot	9872	1025	508	33
120 free	2245	233	48	3
110 + 120 tot	12117	1258	557	36
- rural + urban			12674	1294
share Heavy Goods Vehicle	0,104			0,064
share rigid truck	0,024			0,015
share truck combinations	0,080			0,049

Truck rates are only assumed to vary with road environment and with a constant relation between rigid and truck combinations in these estimates. Truck rates are 10.4% in rural and 6.4% in urban conditions with rigid trucks 2.4% and 1.5 % and truck combinations 8.0% and 4.9% respectively. The rate truck combinations to trucks is 0.77.

Table 30 Truck type mileage according to VTI.

Truck type/gross	Ratio			
RT petrol	0.1	RT rigid truck		
RT <7.5	2.2	TC truck combination		
RT 7.5-12	2.8	Euro+Nordic		
RT >12-14	0.4			
RT >14-20	6.1			
RT >20-26	2.2			
RT >26-28	10.2			
RT >28-32	2.1			
RT >32	2.2			
RT tot	28.3			
TC >20-28	0.1			
TC >28-34	1.8			
TC >34-40	15.2			
TC >40-50	18.0			
TC >50-60	36.7			
TC tot	71.7			
tot Million veh km	4660			

The Swedish National Road and Transport Research Institute (VTI) (Yahya & Henriksson, 2019) has used vehicle inspection mileage statistic data and a field sample survey to update truck mileage data used for 2015 HBEFA Swedish estimates. Their data is shown in Table 30.

A main purpose was to receive data on foreign registered trucks. Result by truck gross weight and truck type is as follows. The total truck mileage 2015 is estimated to be 4.66 billion truck kilometer. 72% of these are truck combinations, thus 3.2 billion truck and trailer kilometres. The report does not give data by road type and speed limit. The NVDB data (Swedish road data bank) estimated the total truck mileage on 110 and 120 km/h motorways to be around 2 billion thus 43% of the total mileage. 56% truck combinations from NVDB is now compared with 72%.

Estimates of traffic flows and truck combination shares

In order to analyze the overall platooning potential, it is necessary to have data on traffic flows and truck combination shares in the relevant situations. What are the truck combination flows on these 110 and 120 km/h motorways? What do we know about their gross weights? The following sources are available: Swedish Transport Administration (STA) traffic count and weight-in-motion measurements and estimates from Handbook Emission Factors for Road Transport (HBEFA, 2019).

Rigid truck mileages vary (see Table 31) between the WSP estimate of 2.4% and the traffic count samples around 6-7% but truck and (incl. semi) trailer mileages coincide around 8-10%. The ratio of truck combinations of total trucks is clearly higher in the WIM-measures around 0.8 indicating a rigid truck percentage around 2.3% close to WSP. The quality test on truck counts indicated that almost 50% of the registered rigid trucks could be other vehicle types. The NVDB cube count based total mileages and the HBEFA 2018 result are close to each other around 12.8 billion vehicle km. The conclusions are then:

- Articulated truck mileage: $0.085 \times 12.8 = 1.1$ billion km (2018).

- Rigid truck mileage: more uncertain, but in the range $0.024-0.07 \times 12.8 = 0.3$ to 0.8 billion km.

WSP is working on an update of the 2015 report proposing in a preliminary version higher figures for both “truck types”. Bad weather and interchange areas should be withdrawn from this figure but are judged to be of at least second order. One-directional traffic volumes in peak hours are as medians around 1 300 vehicles/hour with a few extremes up to the double.

WIM average gross weights (2018) were 12 for rigid trucks, 19 for buses (with an over all rigid average 13), 30 for semi trailers and 41 tons for truck and trailers. HBEFA reports 18 for rigid trucks and 35 as an average for semis and truck and trailers. The latter coincide well but there is a large discrepancy for rigid trucks.

Table 31 Summary shares of rigid and articulated trucks according to indicated source.

Source	Shares of total traffic			TC truck share
	RT	TC	RT+TC	TC/(RT+TC)
Effect catalogue STA	6	8	14	0.57
Traffic count samples STA	7	9	16	0.56
WSP	2.4	8	10.4	0.77
E4 WIM STA				0.82
E6 WIM STA				0.75

A.3 Speed and manual platooning behavior

Rigid truck/bus and truck and truck combination speed behaviour (km/h) on 4 lane motorways with good alignment (sight class 1) due to one directional total traffic flow (vehicles/hour) at 110 and 120 km/h is modelled as in Figure 15 and Figure 16 based on empirical data and traffic simulations in the Swedish Transport Administration Effect Catalogue (Trafikverket, 2018) (see also (Olstam & Bernhardsson, 2017), (Olstam, Carlsson, & Yahya, 2013), (Forsman & Greijer, 2016)).

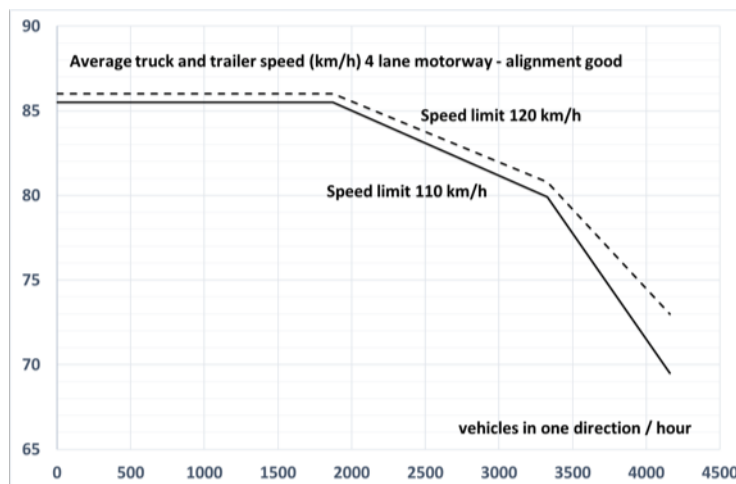


Figure 15 Truck combination average travel (space mean) speed (km/h) due to traffic flow (vehicles/hour one direction) according to (Trafikverket, 2018) on 4 lane motorway 110 and 120 km/h speed limit.

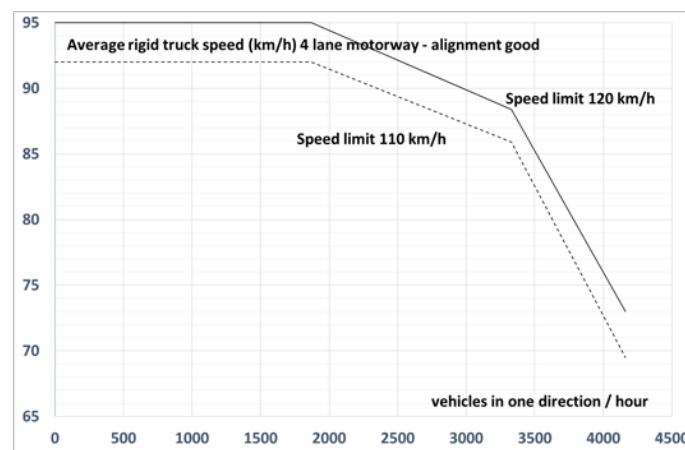


Figure 16 Average speed (km/h) for rigid trucks and buses due to traffic flow (vehicles/hour one direction) according to (Trafikverket, 2018) lane motorway 110 and 120 km/h speed limit.

Legal speed limits on 110 and 120 km/h motorways are 90 km/h for rigid trucks, 80 km/h for truck combinations and 100 km/h for buses. Trucks and buses over 7.5 tons are required to have speed regulators strangling the engine at 90 for trucks and 100 for buses. Bus shares are normally around 15% of rigids corresponding with around 1 km/h lower speed for rigid trucks only. The share of rigid trucks without speed regulators is some 30% to 40%. Average speeds exceed the legal speed limit all the way up to a one-directional traffic flow of some 3 000 vehicles/hour at good road surface, day light conditions and a good alignment.

It seems to be a common opinion in the business that “manual platooning” is quite common. There are however no surveys available addressing current “manual platooning” of trucks, when drivers use a short gap without technological aids. There are some measurements on gross and axle weights and lengths, not stratified by lane, that might be used to get some information:

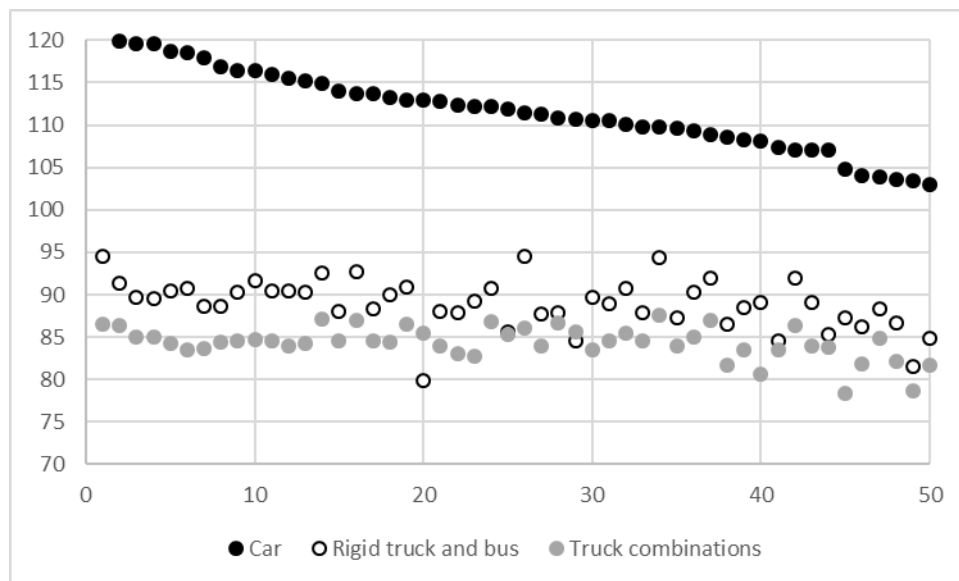


Figure 17 Rigid Sample daily 50 highest car averages (2014, 15) E4 and E6 with corresponding truck speeds without and with trailer.

Sample measurements by day of the average speeds for cars and trucks without trailer and truck combinations for the 50 highest car flow values on E4 and E6 are shown in Figure 17. There is obviously a rather big variation around the model average due to location and weather/surface conditions.

Truck performance at long up-hills and while overtaking can create capacity problems inducing shock waves due to major speed differences compared with other traffic. Uphill behaviour depends on entering speed, weight-power ratio, air resistance coefficient, frontal area and grade and length of the up-hill as shown in Figure 18, Figure 19 and Figure 20, from the road design guidelines VGU (Trafikverket, 2015). VGU values are 6.0 W/kg for power weight ratio; 0.500 kg/m³ for air resistance; 6.5 m² for frontal area; and 31.5 tons for gross weight.

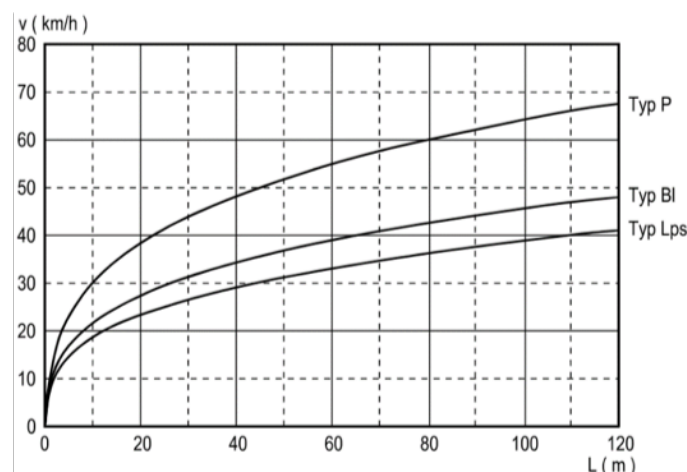


Figure 18 Truck and trailer up hill (Lps) acceleration speed behaviour according to VGU due to entering speed and up hill length in meter (längd) at 0% grade.

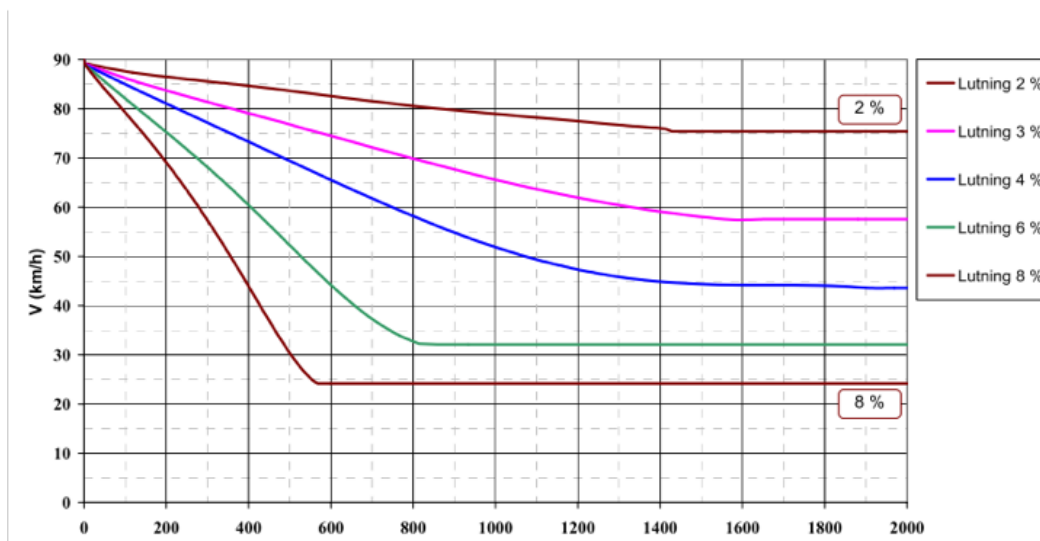


Figure 19 Truck combination up hill retardation speed behaviour according to VGU due to entering speed and up hill length in meter (längd) and grade % (lutning).

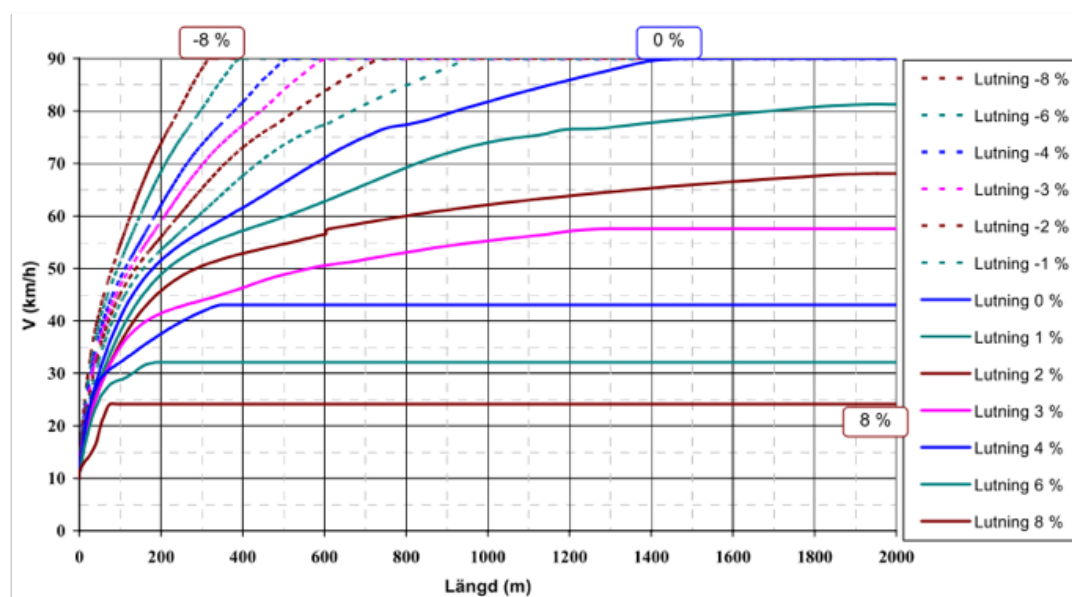


Figure 20 Truck combination up hill acceleration speed behaviour according to VGU due to entering speed and up hill length in meter (längd) and grade (lutning) %.

There are a number of longer up hills on Swedish rural motorways such as south of Jönköping on E4, E6 Hallandsåsen and E6 north Landskrona creating very low truck combination speeds and thus sometimes creating shock waves and capacity and also safety problems. There are also some sections where truck overtaking each other with minor speed differences blocks the overtaking lane also creating shock waves. The present measure to deal with these problems are in Sweden local overtaking prohibitions for trucks.

A.4 Fuel consumption

The Transport Administration model for the relation between fuel consumption, average truck speed and road alignment described as sight class in the EVA-package (software based on Effektkatalogen) still relies on the VETO model (Carlsson & Hammarström, 2008). The alignment impact is strong as seen in the two graphs below for rigid truck and truck combination (Trafikverket, 2018). Data for rigid trucks are shown in Figure 21 while truck combination data can be found in Figure 22.

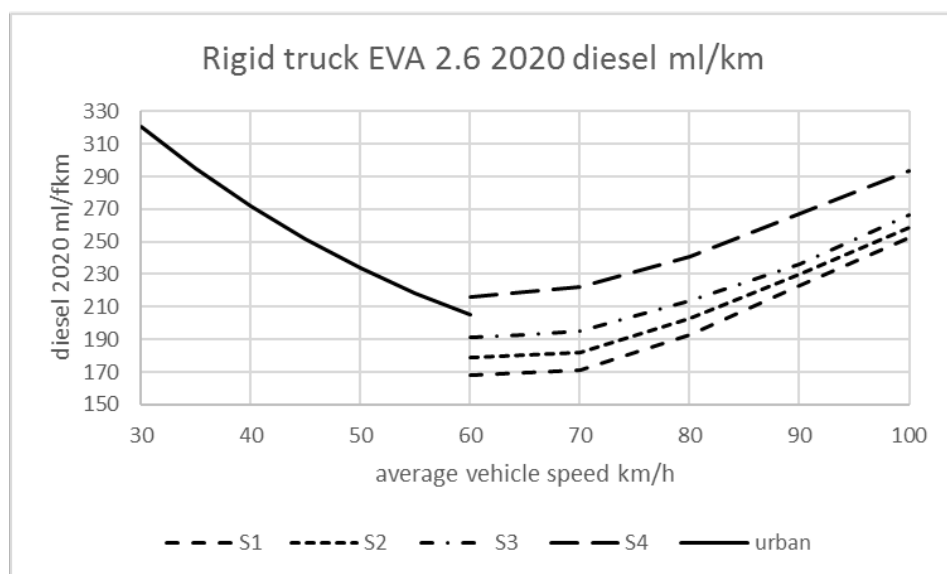
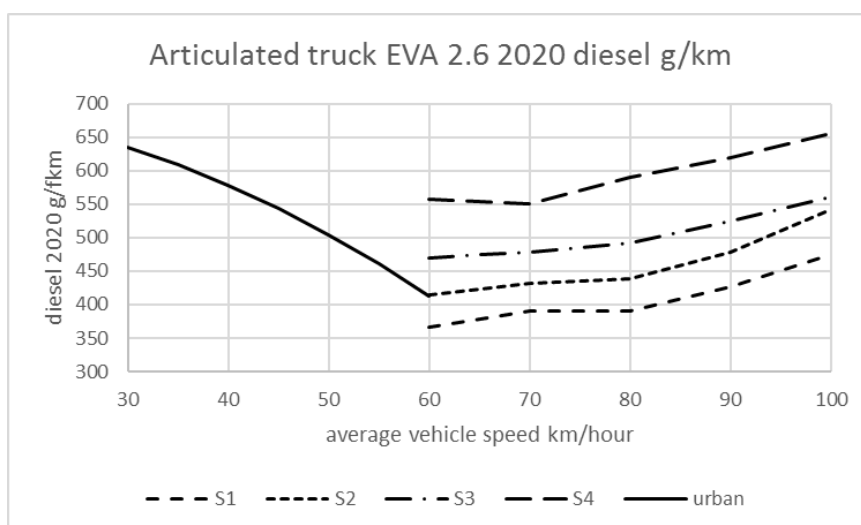


Figure 21 Rigid truck average fuel consumption due to average rigid truck speed and sight class.

Figure 22 Articulated truck (truck combination) average fuel consumption due to average speed and sight class.



Fuel consumption is lowest at average speeds around 60 km/h and increases with both decreasing (in urban environment due to speed changes forced by accesses, traffic friction etc) and increasing average speed with a major impact of sight class. Motorway

speeds (with sight class 1 to 2) are around 94 km/h for rigid trucks and 85 km/h for truck combinations with fuel consumption levels around 220 and 450 ml/truck km. These levels are obviously heavily dependent on vehicle data (6 kg/W, weight around 40 ton, air resistance 0.7, front area around 9 m², Euro 1-3 in the EVA model) and these sight classes, see Table 32. The average absolute grade in sight class 1 is around 0.7% and in 2 up to 1.5% in the model.

Table 32 VTI sight classes according to VTI.

sight class	ADC	RF
S 12	1.5	5.5
S 21	9.8	15.4
S 22	29.8	5.0
S 3	17.5	17.6
S 41	85.6	18.3
S 42	42.4	30.0
ADC=angle change degree/km		
RF=absolute height change m/km		

Alignment data is available in the PMS (Pavement Management System) data bank. VTI calculated alignment (*i.e.*, horizontal and vertical curvature) distributions for motorways over all speed (Björketun, 2003) see. Table 33, due to absolute horizontal angle changes (rad/km) and vertical rise and fall (m/km). 75% have an average rise and fall less than 10 m/km, 21 between 10 and 20 and 4% over 30. The average rise and fall lies in the range 0.7% to 0.8%.

Table 33 Motorway alignment classes according to VTI, showing the absolute value in radians of the grade.

Abs rad/km	Rise and fall abs m/km		
	<10	10-30	>=30
<0,5	46	6	1
0.5-1.25	29	14	1
>=1.25	0	1	2

VTI has tried to modernize the EVA speed and sight class model using the PHEM-model truck representation and HBEFA driving patterns instead of the VETO sight classes/alignments for sight class 1 to 3 (Janhäll, Carlson, & Larsson, 2017). Results are described by speed limit, *i.e.*, not actual average truck speed and are separated by Euro class, see graphs below for sight class 1 and 2 for rigid and articulated trucks. Driving patterns have been changed compared with VETO/EVA not accepting speeding, see rigid truck speed limit 90 below. These speeds are much lower than actual Swedish motorway speeds with and average around 95 for sight class 1 and 93 for 2, as shown in Figure 23.

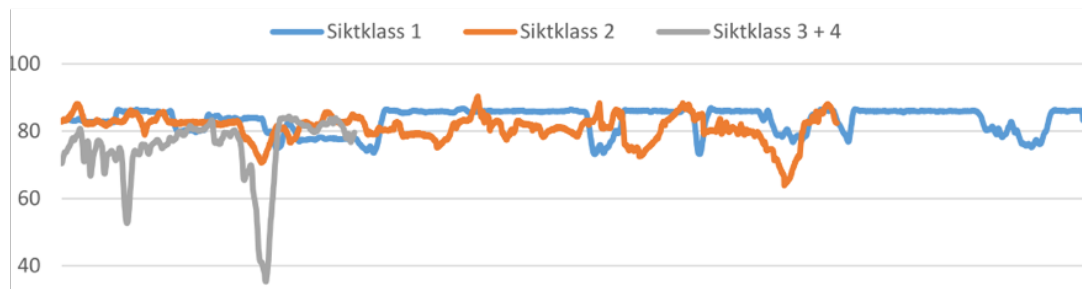


Figure 23 Driving pattern (longitudinal speed variation as a function of time) for truck due to sight class.

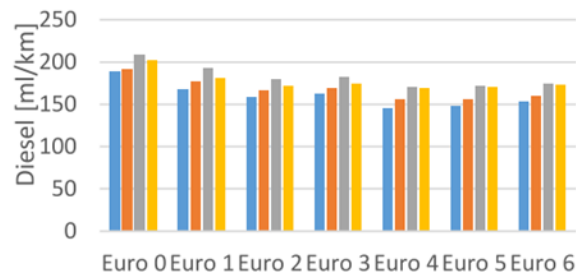


Figure 24 Rigid truck average fuel consumption due to speed limit (60, 70, 80, 90 from left) and Euro class speed sight class 1.

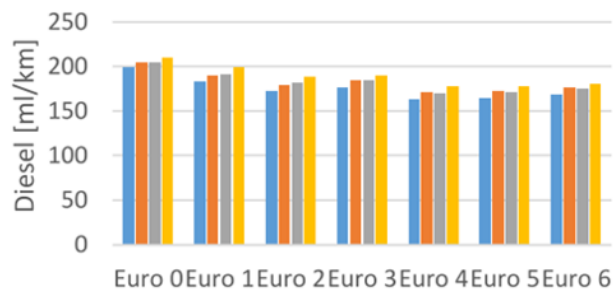


Figure 25 Rigid truck average fuel consumption due to speed limit (60, 70, 80, 90 from left) and Euro class speed sight class 2.

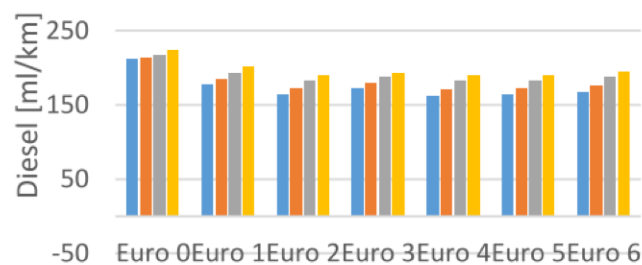


Figure 26 Rigid truck average fuel consumption due to speed limit (60, 70, 80, 90 from left) and Euro class speed sight class 3.

Rigid truck fuel consumption decreases substantially with speed limit from Euro 1 to Euro 3. Consumption increases with speed limit up to 80 then to decrease for sight class 1 (Figure 24) but increases with speed limit for the other sight classes (Figure 25 and Figure 26). The impact of sight class is minor between 1 and 2 but major between 2 and 3. The sight class 1 and 2 average for speed limit 90 km/h varies from 200 ml/km to 170 due to Euro class. The old model gives 190 to 230 ml/km depending on actual speed (80 to 95) given 2020 Euro class mix.

Truck combination fuel consumption does not decrease substantially with speed limit from Euro1 to Euro 3 as rigid truck consumption does. Consumption increases with speed limit up to 80 in the same way as for rigid trucks. The impact of sight class is minor between 1 (Figure 27) and 2 (Figure 28) but major between 2 and 3 (Figure 29). The sight class 1 and 2 average for speed limit 90 km/h varies from 430 ml/km to 380 due to Euro class. The old model gives 190 to 230 depending on actual speed (80 to 95) given 2020 Euro class mix.

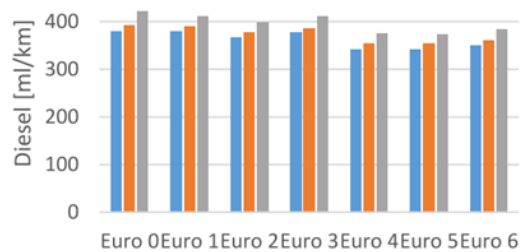


Figure 27 Articulated truck average fuel consumption due to speed limit (60, 70, 80 from left) and Euro class speed sight class 1.

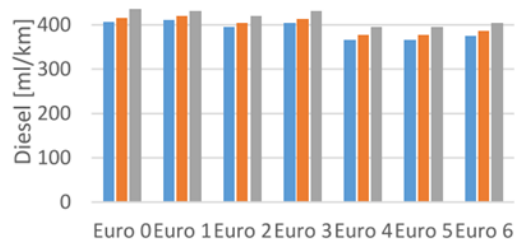


Figure 28 Articulated truck average fuel consumption due to speed limit (60, 70, 80 from left) and Euro class speed sight class 2.

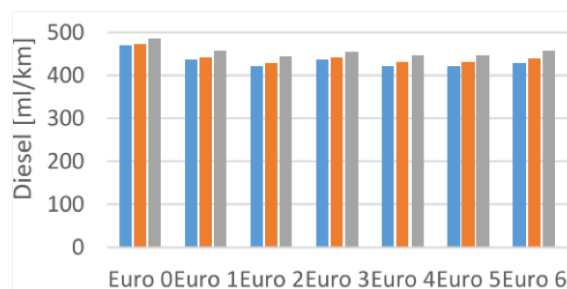


Figure 29 Articulated truck average fuel consumption due to speed limit (60, 70, 80 from left) and Euro class speed sight class 3.

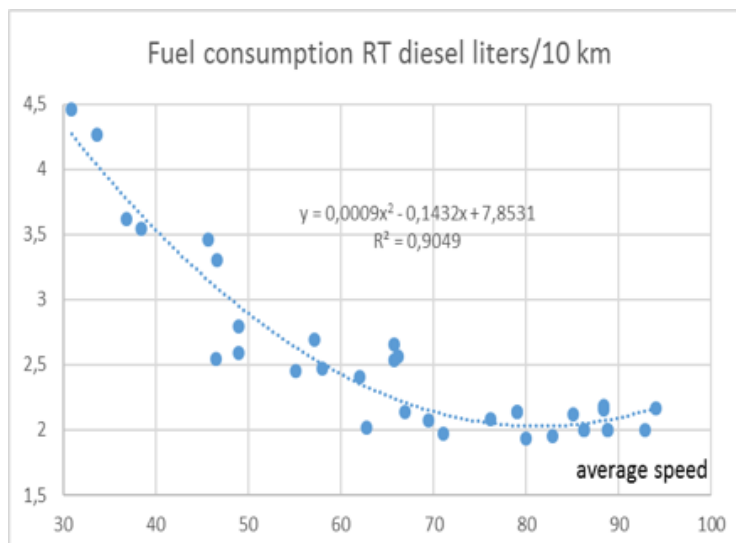


Figure 30 Truck combination average fuel consumption due to actual speed according to Swedish Transport Administration.

The Swedish Transport Administration has developed a speed-fuel consumption model, so far not published, using HBEFA data, see Figure 30 and Figure 31. The fuel consumption level is down at around 3 liters/10 km, *i.e.*, far below the models described above. Questions and discussions with the Swedish Transport Administration have not revealed any explanations to the major differences.

The marginal speed effect in the interval from 80 to 86 km/h is 22 to 34 ml per km/h per km compared with 35 to 40 in the present EVA/VETO-model for truck combinations. The corresponding figures for rigid trucks in the interval from 90 to 96 km/h is 20 to 29 ml per km/h per km compared with around 30 in the present EVA/VETO-model for rigid trucks.

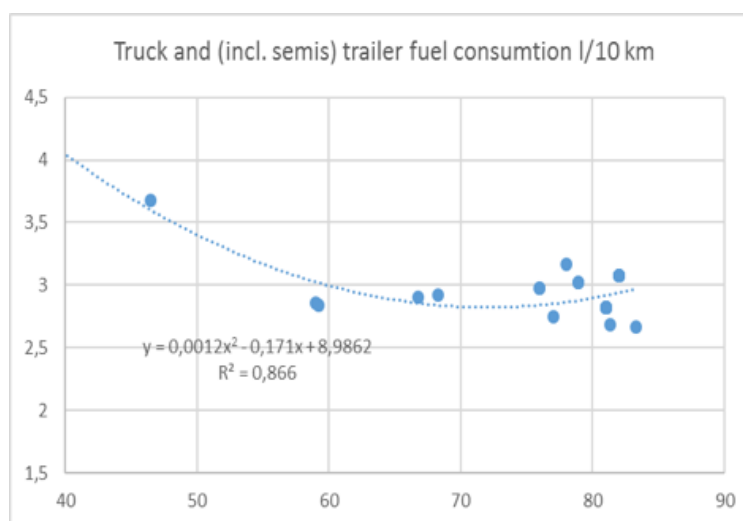


Figure 31 Enlarged view of part of Figure 30.

The HBEFA results shown in Table 34 were delivered by Yahya (Yahya, 2019) for Swedish average diesel consumptions for rigid trucks and truck combinations for a flat road (0% grade) and for a road that combines equal sections of uphill (2% grade) and downhill (-2% grade). In the latter case, both sections were driven at creeping speed for these grades. A reasonable average for Swedish motorways is 0.75%. The latter gives an average around 3.4 liters per 10 km for truck combinations and 2.3 liters for rigid trucks.

Table 34 HBEFA results according to Yahya with Swedish data.

Grade	Type	Euro-0	Euro-I	Euro-II	Euro-III	Euro-IV	Euro-V	Euro-VI	Mean
0%	RT	2,25	1,93	2,04	2,22	2,17	2,18	2,34	2,25
	TC	3,41	3,10	3,07	3,14	2,99	2,94	3,09	3,04
+2%	RT	2,36	2,03	2,16	2,33	2,38	2,40	2,56	2,47
	TC	3,98	3,69	3,74	3,80	3,82	3,82	3,97	3,91
+0,5%	RT	2,27	1,96	2,07	2,24	2,22	2,23	2,39	2,31
	TC	3,55	3,25	3,23	3,31	3,19	3,16	3,31	3,25

TC= truck combination RT= rigid truck

A question to Sveriges åkeriföretag gave the following information:

- An international (4 m height) Nordic combination (latest model) with truck and load weight 45-48 ton consumes slightly over 3 liter/10 km at 82 km/h. A couple of deciliters should be added should the height be 4.5 m.
- A Swedish haulage contractor company using trucks (brand new) with dolly trailer consume 3.5-3.7 liter/10 km with 60-64 ton average with optimal conditions (speed information missing).
- Another Swedish haulage contractor company with brand new trucks carrying on average 82 km/h consume between 4.2 and 4.8 liter/10 km with an average of 4.6 and with an average truck and load weight of 58 ton.
- 3.1 liter/10 km with an average gross weight of 40 tons not impossible to reach given ideal conditions.

Volvo and Scania project assumptions on fuel effects of platooning assumes a fuel consumption level around 3 liters/10 km, see Chapter 4.

A.5 Safety effects for other vehicles data

What do we know about truck safety on motorways?

The Swedish Transport Administration has recently merged police reported accidents from Strada (the accident data bank) with road and traffic data from NVDB (the road data bank) to produce risks by vehicle and accident type stratified by road type, speed limit, speed cameras, road and median width for the time periods 2009 to 2013 and 2015 to 2017. Data for accidents, fatalities, severe and light injuries (police information) and mileages with heavy trucks involved are given in Table 35 for motorways with speed limits 110 and 120 km/h. Truck mileages are estimated using the 16% assumption in chapter 2. Average risks (per million truck kilometers) are systematically higher at motorways with speed limit 120 km/h. Standard procedures can not differ between rigid trucks and truck combinations.

Table 35 Motorway 110 and 120 km/h accident data and risks 2015-17 and 2009-13 with heavy trucks involved homogenized data speed limit, road type, sped cameras, road and median width.

Motorway		Police data (homogen. by speed, road type, total and median width)							Per Million truckkm				
Speed	Year	Accidents	Fatalities	Severe	Light	Mvkm	Mapkm	Mtruckkm	Acc	F	S	F+S	L
110	15-17	401	5	29	221	29845	34592	4775	0,084	0,0010	0,0061	0,0071	0,046
120	15-17	77	2	5	54	6019	7319	963	0,080	0,0021	0,0052	0,0073	0,056
110	09-13	696	7	45	452	46033	53280	7365	0,094	0,0010	0,0061	0,0071	0,061
120	09-13	179	1	18	102	9854	12074	1577	0,114	0,0006	0,0114	0,0121	0,065
110	tot	1097	12	74	673	75878	87872	12140	0,090	0,0010	0,0061	0,0071	0,055
120	tot	256	3	23	156	15873	19392	2540	0,101	0,0012	0,0091	0,0102	0,061
		truck % = 16 % of mileage											

These statistics can be compared with data for accidents without heavy trucks involved, see Table 36. The risk picture (per million non-truck km) is less clear here with higher 120 km/h risks for severe injuries and fatal and severe injuries but otherwise contrary with small differences.

Table 36 Motorway 110 and 120 km/h accident data and risks 2015-17 and 2009-13 with heavy trucks not involved homogenized data speed limit, road type, sped cameras, road and median width.

Motorway exc truck		Police data (homogen. by speed, road type, total and median width)							Per Million veh km				
Speed	Year	Accidents	Fatalities	Severe	Light	Mckm			Acc	F	S	F+S	L
110	15-17	1165	17	218	1824	25070			0,046	0,0007	0,009	0,009	0,073
120	15-17	200	3	64	239	5056			0,040	0,0006	0,013	0,013	0,047
110	09-13	2368	53	467	3727	38667			0,061	0,0014	0,012	0,013	0,096
120	09-13	510	9	171	758	8277			0,062	0,0011	0,021	0,022	0,092
110	tot	3533	70	685	5551	63737			0,055	0,0011	0,011	0,012	0,087
120	tot	710	12	235	997	13333			0,053	0,0009	0,018	0,019	0,075

The risk ratio between truck accidents and non-truck accidents are calculated in Table 37. The truck accident risk and the truck light injury risk are higher. Severe injury and fatal and severe injury risks are close to each other though slightly higher for non-truck accidents. Fatalities and injuries in truck accidents are mostly drivers and passengers in cars, not in the trucks.

Table 37 Motorway 110 and 120 km/h accident data and risks 2015-17 and 2009-13 with heavy trucks not involved homogenized data speed limit, road type, sped cameras, road and median width.

Speed	Year	Trucks/non trucks				
		Acc	F	S	F+S	L
110	15-17	1,81	1,54	0,70	0,76	0,64
120	15-17	2,02	3,50	0,41	0,55	1,19
110	09-13	1,54	0,69	0,51	0,53	0,64
120	09-13	1,84	0,58	0,55	0,55	0,71
110	tot	1,63	0,90	0,57	0,60	0,64
120	tot	1,89	1,31	0,51	0,55	0,82

Truck accidents on E4 Helsingborg-Stockholm and E6 Trelleborg-Göteborg at 110 and 120 km/h speed limit 2009-2017 are given by accident type and outcome in numbers and ratios are shown in Table 38.

Table 38 E4 and E6 110 and 120 km/h accident data 2009-2017 with heavy trucks involved by accident type and outcome (number of accidents, fatalities, severe and light injuries).

Police reported truck acc 2009-17	E4 Helsingborg-Stockholm				E6 Trelleborg-Göteborg			
	Acc	Fat	Sev	Light	Acc	Fat	Sev	Light
Turn off multi motor vehicles					1	1	0	0
Pedestrian- motor veh	4	2	2	1	3	3	0	0
Pedestrian-pedestr.	1	0	0	2				
Crossing motor vehicles	1	0	1	1	1	0	0	1
Head on motor vehicles	2	0	0	4	2	0	1	2
Overtaking motor vehicles	38	0	5	43	18	0	2	20
Single run off motor vehicles	56	4	4	51	27	1	2	26
Rear end motor vehicles	161	6	41	208	147	8	50	181
Other	14	3	3	13	12	0	7	16
Parking	7	0	0	10	8	0	1	9
Prohibited movement	3	0	2	2	5	0	2	6
Total	287	15	58	335	224	13	65	261

Acc=accidents Fat=fatalities Sev= severe injuries Light= light injuries

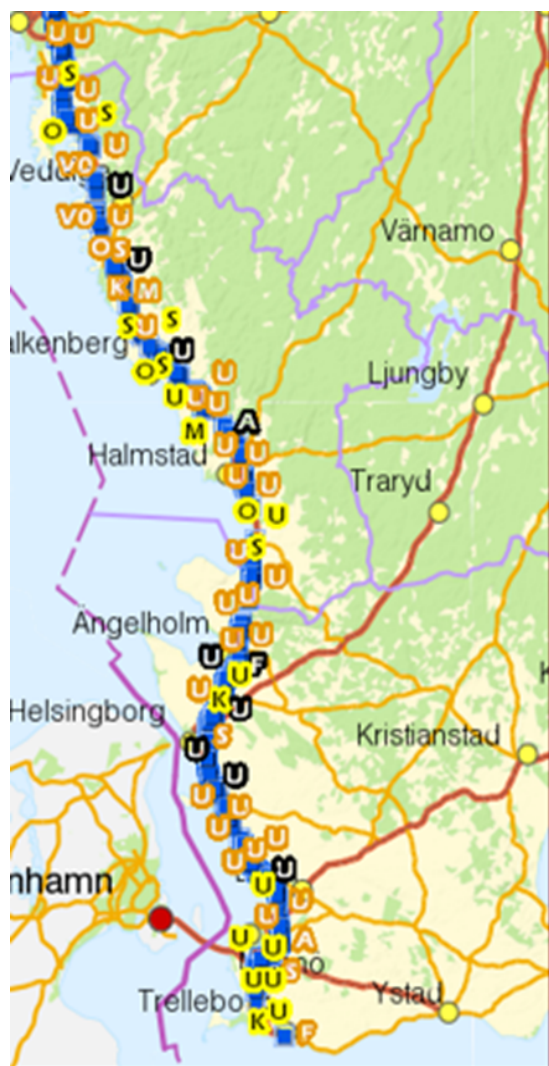
Rear end is by far the most common accident type with 56% and 66% of the accidents, 40% and 62% of the fatalities, 71% and 77% of the severe and 62% and 69% of the light injuries respectively on E4 and E6. The rear end type mostly also include multi vehicle lane change accidents, very common at high flows. Overtakings and single run offs are in the range around 10% higher on E4 than E6. E4 and E6 110 and 120 km/h accident data 2009-2017 (Table 39) with heavy trucks involved by accident type and outcome (ratios for accidents, fatalities, severe and light injuries).

Table 39 E4 and E6 110 and 120 km/h accident data 2009-2017 with heavy trucks involved by accident type and outcome (ratio for accidents, fatalities, severe and light injuries).

Police reported truck acc 2009-17	E4 Helsingborg-Stockholm				E6 Trelleborg-Göteborg			
	Acc	Fat	Sev	Light	Acc	Fat	Sev	Light
Turn off multi motor vehicles	0,00	0,00	0,00	0,00	0,00	0,08	0,00	0,00
Pedestrian- motor veh	0,01	0,13	0,03	0,00	0,01	0,23	0,00	0,00
Pedestrian-pedestr.	0,00	0,00	0,00	0,01	0,00	0,00	0,00	0,00
Crossing motor vehicles	0,00	0,00	0,02	0,00	0,00	0,00	0,00	0,00
Head on motor vehicles	0,01	0,00	0,00	0,01	0,01	0,00	0,02	0,01
Overtaking motor vehicles	0,13	0,00	0,09	0,13	0,08	0,00	0,03	0,08
Single run off motor vehicles	0,20	0,27	0,07	0,15	0,12	0,08	0,03	0,10
Rear end motor vehicles	0,56	0,40	0,71	0,62	0,66	0,62	0,77	0,69
Other	0,05	0,20	0,05	0,04	0,05	0,00	0,11	0,06
Parking	0,02	0,00	0,00	0,03	0,04	0,00	0,02	0,03
Prohibited movement	0,01	0,00	0,03	0,01	0,02	0,00	0,03	0,02
Total	287	15	58	335	224	13	65	261

Acc=accidents Fat=fatalities Sev= severe injuries Light= light injuries

There are 26 multi truck accidents on E6 (see Figure 32 and only 12 on E4. The reason is probably the long up hills at Landskrona and between Helsingborg and Halmstad.



Legend:

Black = fatal accident

Red = serious accident

Orange = moderate accident

Yellow = light accident

According to Strada classification usin I:

U = rear end

S = run off

A = turn off

O = overtaking

K =crossing

Figure 32 E6 accidents by type and severity according to Strada.

“Snowy/icy” and moisty conditions have some 20% each on E4 and 8 and 25% on E6, see Table 40.

Table 40 E4 and E6 110 and 120 km/h accident data 2009-2017 with heavy trucks involved by accident type and outcome (ratios for accidents, fatalities, severe and light injuries).

Surface	E4 Helsingborg-Stockholm				E6 Trelleborg-Göteborg			
	Acc	Fat	Sev	Light	Acc	Fat	Sev	Light
"snowy/icy"	0,25	0,13	0,21	0,27	0,08	0,00	0,07	0,08
snowy	0,10	0,00	0,07	0,10	0,05	0,00	0,07	0,05
unknown	0,01	0,00	0,00	0,01	0,04	0,00	0,01	0,04
ice/thick snow	0,05	0,00	0,05	0,05	0,00	0,00	0,00	0,01
icy, surface visible	0,10	0,13	0,09	0,11	0,02	0,00	0,00	0,02
dry	0,52	0,53	0,64	0,55	0,62	0,87	0,60	0,61
moisty	0,22	0,33	0,16	0,17	0,26	0,13	0,31	0,27
total	287	15	58	335	392	15	86	462

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