

# Study of communication needs in interaction between trucks and surrounding traffic in platooning



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## 1 Sammanfattning

I en nära framtid kommer platooning med stor sannolikhet bli vanlig på svenska vägar och potentialen för bränslebesparing i transportsektorn är stor. Det finns emellertid frågetecken kring hur lastbilar i platoon och omgivande trafik påverkar varandra. Under demonstrationsprojektet European Truck Platooning Challenge (ETPC) framkom behov av att kunna kommunicera med omgivande trafik för att undvika att platoonen bryts upp och fördelarna med bränslebesparing går förlorade. Detta projekt avser utreda behovet av extern signalering mellan lastbilar i platoon och omgivande trafik i syfte att bibehålla fördelarna med platooning i så många trafiksituationer som möjligt, samt främja acceptans och upplevd trygghet hos omgivande trafik.

## 2 Executive summary

Platooning will soon likely to be common on Swedish roads and the potential for fuel savings in the transport sector is high. This pre-study project explores the need for external signaling in platoons to avoid any cut-ins from surrounding vehicles whose drivers are unaware that their actions may cause a loss of fuel saving.

Interviews with truck drivers created an understanding of how they experience the behavior of the surrounding traffic. The scenarios that are highlighted where unaware cut-ins may occur are mainly on-ramps and while overtaking on highway. Car drivers highlighted that overtaking may be a problem, especially on 2+1 roads. Communication needs elicited in workshops with drivers mainly concerned the movement patterns and properties of vehicles, e.g. speed, direction, gaps and length of the platoon.

Barriers that were identified for external signaling is that trailers are constantly rotating between different tractors. This may require that more trailers than tractors need to be equipped with communication devices.

To evaluate the potential impact of external signaling simulation could be used, where a driving simulator could be used to evaluate the perception of car- and truck drivers. Different means of communication, behavior, driving close together or lighting could be subject to evaluation. The long-term learning effect and behavioral adaptation to platooning in traffic is also important to study.

It was found that there are large regional behavioral differences in traffic. Naturalistic data from the US, indicate that there are no cut-ins if the distance between trucks is < 30 m. In Europe, the data collected from ETPC indicate that there is up to one cut-in every 15 km on highways. The data from the ETPC is however very sparse compared to the US study.

In Sweden, it does not seem to be a specific need for external signaling since very few cut-ins occur. In Europe, more cut-ins occur and external signaling could help to save fuel. It is however unclear what long-term effects external signaling may have. Further studies are suggested to study if short platooning distance (10-20 meters) is sufficient to deter surrounding traffic from cut-ins.

## 3 Introduction

### 3.1 Background

In the near future, platoon driving will most likely be common on Swedish roads and the potential for fuel savings in the transport sector is high. As part of this development, the European Truck Platooning Challenge (ETPC) was recently conducted to demonstrate and test platooning in real traffic [2]. The evaluation of the ETPC showed that there are traffic conditions on the highway in which it is difficult to maintain the platoon without adversely affecting the surrounding traffic. If the platoon needs to be broken up, the benefits of fuel saving and more efficient road use are likely to decrease. At the same time, acceptance of platooning in surrounding traffic may also be adversely affected if platoon and other traffic do not interact effectively and safely, providing an experience of safe interaction. This project therefore intends to investigate:

- 1) how interruptions of platoons are reflected in fuel consumption, and
- 2) how interruptions are experienced by platoon drivers and other road users and
- 3) what new communication needs may exist between platoon and surrounding traffic.

#### *Evaluation of the European Truck Platooning Challenge*

The ETPC was conducted with leading truck manufacturers that drove from different European cities to Rotterdam to demonstrate platooning in real-world traffic. In connection with the ETPC, the Rijkswaterstaat made an assessment that, among other things, showed that external signaling is wanted by truck drivers in order to signal the Platoon's intentions and actions to surrounding traffic. This issue was raised because traffic in certain motorway situations often cut-in between the vehicles in the platoon. Even in the case of motorway roads, there was a desire to be able to inform the surrounding traffic that the trucks on the highway are part of a platoon and that there is therefore an intention for trucks to drive very close. The evaluation was based on interviews with participating organizations and drivers. However, in this evaluation, the needs from those who meet a platoon, i.e. drivers of vehicles in the surrounding traffic, was not assessed.

#### *The benefit of platooning*

The advantages of platooning are mainly lower fuel consumption and more efficient road use. Intensive development of technology is ongoing at truck manufacturers to take platooning to the market. If the platoon often needs to be split because of other road users interfering between trucks or that drivers themselves feel that they need to increase the distance so as not to hinder surrounding traffic, then the benefits of platooning may be lost in some situations. However, it is unclear how much this impact is on the overall benefit. By using data recorded under ETPC, an assessment can be made of how much savings are likely to be lost due to interrupted platoons. Thus, potential benefit of external signaling and alternative driving modes to avoid breaking the platoon can also be evaluated.

### 3.2 Purpose and Research Questions

The main purpose of the project is to investigate how interruption of platoons affect fuel consumption and to investigate the communication needs that exist when driving in a truck platoon. The project hopes to understand how to maintain the benefits of platoon driving without adversely affecting surrounding traffic.

The two overall research questions are:

- 1) What information needs to be communicated from platoon to surrounding traffic to create safe and efficient interaction with surrounding traffic?
- 2) How is the platoon fuel consumption affected by cut-ins into the platoon?

### 3.3 Aim

The aim of the project is to:

- Map and follow up experiences from previous platooning projects and activities (with regards to external signaling)
- Obtain the needs for communication between platoons and surrounding traffic
- Define use cases and criteria for future evaluation of external signaling
- Judge the fuel saving benefit of avoiding the platoon to dissolve

## 4 Method

### 4.1 Research approach

The overall idea of this pre-study project is to assess if and how vehicles that belong to a platoon should inform the surrounding traffic, for example the intentions of a platoon and how many vehicles that belong to it. The communication must probably primarily be visual, as traffic in the foreseeable future mainly consists of vehicles without the possibility of V2V communication (V2V communication is not included in this project). These communication needs should be investigated, partly from truck drivers, and from surrounding road users' experiences to achieve efficient and safe interaction.

### 4.2 Procedure

The project was divided into four work packages.

#### *WP 1 - Needs identification from drivers' perspective*

Work package 1 identified needs based on the driver's perspective, considering both truck drivers and drivers of other vehicles in surrounding traffic. These actors are the ones who will activate and also understand the signaling from a platoon. To assess platoon driving in real traffic (staged or simulated) is an extensive and costly activity that has been outside the scope of this pre-study project. Therefore, other methods have been used to find out the drivers' needs i.e. workshops and interviews. Through this method, participants were given the opportunity to reason and on the basis of this reasoning, communication needs were specified. We reached out to truck drivers who participated in ETPC, as well as experienced drivers of other types of vehicles, such as passenger cars and other truck drivers.

- Research questions WP1:

What communication needs are there with the drivers of platoon truck drivers and with drivers of other types of vehicles respectively, in order to ensure safe and efficient interaction between a truck platoon and surrounding traffic?

- Delivery from WP1:

Specification of driver's communication needs in (i) interaction between drivers in platoon and (ii) drivers of other vehicles.

### *WP 2 - Needs identification with other actors*

In work package 2, a mapping with organizations that participated in ETPC was done with for example, OEMs, regulatory bodies and other stakeholders. The project also contacted Peloton in the United States to receive the views of a platooning technology provider. The aim is to identify the possibilities and possible barriers that exist in the future implementation of external signaling for vehicles in platoon based on a socio-technical perspective.

- Research question WP2:

What are the needs of different actors (not drivers) in the future implementation of external signaling in order to achieve effective interaction with surrounding traffic when driving in a platoon?

- Delivery from WP2:

Mapping various actors' needs about how trucks in the platoon should interact with surrounding traffic and what barriers may exist in the future implementation of external signaling.

### *WP 3 - Methodology and use cases for future evaluation*

The purpose of AP3 was to develop proposals for methodology and use cases for future evaluation of concepts for external signaling. In this project, no specific work was done to develop conceptual proposals for external signaling from platoons, but some ideas that came forward during the work have been documented. Irrespective of possible future concepts from the OEMs', these ideas will have to be evaluated which motivates the work done in WP3. If the results from WP1 show that there is no need for external signaling on truck platoons, then interaction between platoons and surrounding traffic will still have to be studied in order to design e.g. platoon motion patterns and appropriate behavior, since the behavior of the platoon becomes a mode of communication itself that is to be interpreted by surrounding traffic.

Experimental evaluation of the concept and / or platoon behavior in a real, staged or simulated traffic environment requires large resources that did not fit within the budget of the project.

- Research question WP3:

Which evaluation methods, use cases, and evaluation criteria are appropriate for evaluating interaction with surrounding traffic when driving in platoon with regard to efficiency and perceived safety?

- Delivery from WP3:

Description of methodology and use cases.

### *WP 4 - Use case: Fuel saving*

In order for a platoon to maintain the estimated fuel savings, it is important to reduce the number of intentional/ unintentional interferences made by vehicles penetrating the platoon. This work package investigates the fuel saving potential of avoiding the platoon to dissolve. By creating a model for fuel saving during platooning the potential loss of fuel saving can be calculated. Data collected by Volvo and Scania from Gothenburg to Rotterdam at ETPC was used to find model parameters such as how long it takes to reconnect after an "interruption" and what speeds are realistic in different traffic situations. The ETPC report from Rijkswaterstaat [2] specifically points out passage through cities with many roads and roads

as problematic to maintain platoon. Additional information about critical situations was also elicited through workshops with professional truck drivers from Volvo and Scania Transport Lab.

By analyzing data from different types of passages, the potential for a signaling system's contribution to fuel economy can be calculated.

The main challenge in the calculations was to find out the range of the parameters to perform calculations of different use cases.

- Research question WP4:  
How can loss of fuel savings due to platoon interruptions be calculated?
- Delivery from WP4:  
A model and analysis of how interference with the platoon affect fuel savings.

## 5 Results and Analysis

The results section is structured according to questions put forward in each work package.

### 5.1 What are the platoon truck drivers' communication needs?

To identify the needs of the truck drivers four different activities were made.

1. Workshops with drivers from ETPC at AB Volvo and Scania
2. Telephone interviews with drivers from ETPC at Iveco and DAF
3. Interview with representative from Peloton, the American company that make aftermarket solutions to be able to drive in platoon with regular trucks ([www.peloton-tech.com](http://www.peloton-tech.com))
4. Interview with Richard Bishop, stand alone consultant who is highly involved with transportation research in the US.

In this section, we present the findings of these activities.

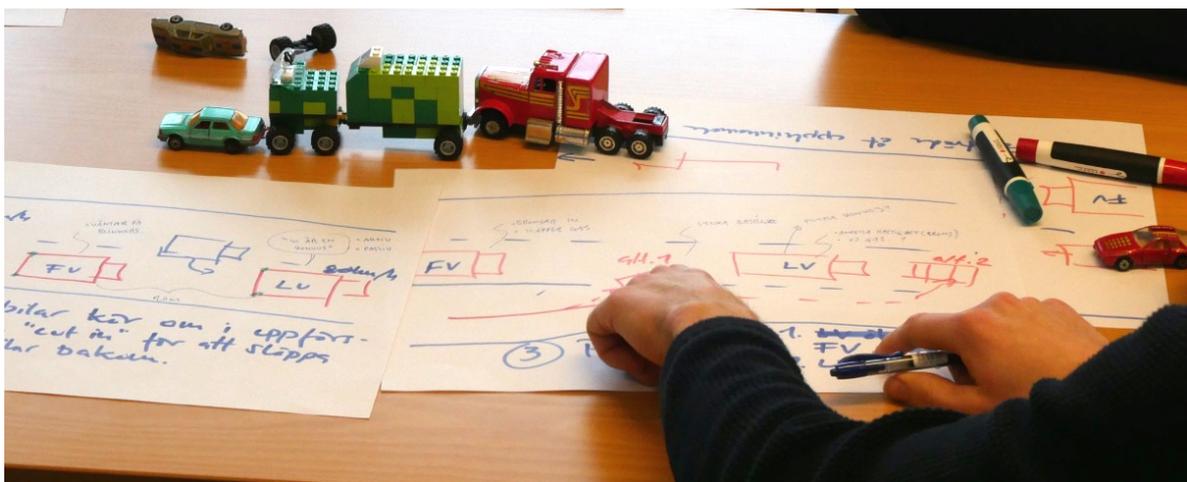


Figure 1. Workshop discussions on platooning scenarios

The discussions in the workshops (1) concerned in what scenarios truck platoon drivers could make use of external signaling to communicate with the surrounding traffic.

The following scenarios were identified:

- When driving on the highway approaching an **on-ramp** where other vehicles will join the highway next to the platoon.
- When driving on the highway approaching an **off-ramp** where overtaking vehicles suddenly want to exit.
- When driving on a highway (that may have on-coming traffic) and there are vehicles behind that want to **overtake**. Also, if a slow vehicle overtakes the platoon a que will form behind creating an incentive for the slow vehicle to cut-in.
- When driving on a highway and one lane is closed for e.g. **roadwork**, the merging vehicles should be aware of the platooning vehicles and that their inter-vehicular distance is short due to their platooning activity.

The needs expressed by the workshop participants are listed in Table 1 below. Many of the needs can be found across situations, but they are listed as found in the workshops. In the needs elicitation part of the workshops, no distinction was made between the means of communication. That is, for example the motion pattern of vehicles can also be seen as a way to communicate intent that meet the drivers need of how to coordinate a traffic situation when platooning. Therefore, based on the list of needs we do not draw any conclusions on whether external signaling is needed in real traffic or not. The purpose is rather to assess drivers' general information need when platooning or encountering a platoon.

Table 1. List of communication needs and what information that may be exchanged between the platoon and surrounding traffic.

Communication needs	Corresponding information
<b>Cruising</b>	
Need to say "We are a platoon" (generic)	The platoon companions show that they are together and drive as one unit
Need to know if you can trust a new platoon companion and to communicate that you are trustworthy	The joining platoon companion communicate its status and performance
<b>On- and Off-ramp</b>	
Need to communicate when it is necessary for one vehicle or the whole platoon to change lanes	The platoon uniformly communicates its intention to change lanes
Need to show when and how to adapt speed to oncoming traffic	The platoon show that it has recognized the oncoming traffic and early show its intended maneuver
Need to communicate which vehicle in the platoon will give way to oncoming traffic	The vehicle shows that it has recognized the oncoming traffic and early show its intended maneuver
Need to tell how to adapt vehicle speed, gaps and position to facilitate weaving with oncoming traffic	The platoon companions indicate its intention to open gap or not
Need to for the oncoming vehicle to sync speed	The platoon indicate its relative speed to the oncoming traffic
Need for the oncoming vehicle to tell that "I expect you to let me in"	The oncoming vehicle communicates its presence, intention and request to join the highway
<b>Overtaking</b>	
Need to communicate time and distance to next off-ramp	The platoon communicates the distance and time to the next off-ramp to aid overtaking decisions
Need to know intention if other vehicle wants to cut-in (to let cars by).	The overtaking truck communicate its intention to let cars from behind pass
<b>Roadwork</b>	
Need to have a lead vehicle driver that is vigilant and can change lane in time when needed.	The lead vehicle indicate its intention to change lane (if uniform lane change, await acknowledgement from companions)

The workshops revealed that there are large regional differences between behavior of **On-ramp** traffic depending on the country. In Sweden for example, other traffic seldom **Off-ramp** with trucks that drive after each other. This is however the case in Europe and the **Overtaking** **Roadwork**

reasons for this are mainly because of the higher traffic rates, there is simply not enough room on the roads and cars, and other trucks, may need to cut-in between trucks that drive close to each other. The other reason is that on-ramps south of the Nordic countries are shorter, typically 400 m in Sweden compared to 250 m Germany, making it harder to make timely entries on the highway when there is heavy traffic.

ETPC data show that cut-ins occur at highways (overtaking) 47%, on-ramps 44%, off-ramps (exits) 7% and lane merge 2%. In the ETPC the number of km between cut-ins was 164,2 km in Sweden, 75,5 km in Denmark, 21,9 km direction south of Netherlands-Belgium and 14,5 km direction north Belgium Netherlands. The mean time a car is between two trucks is 15 seconds.

It should be noted that ETPC was only for a few days and the trucks that generated this data drove one return trip from Gothenburg to Rotterdam, however the numbers indicate that the traffic situation is completely different in Sweden compared to Netherlands and Belgium. Most of the data is collected while driving with ACC with 1 s time headway resulting in a following distance of about 22 m. The drivers did not notice any particular behavior difference among the surrounding traffic when the time headway was changed to 1.3 s. It should also be noted that the data includes several experiments made during the ETPC, where the system was evaluated while escort cars made cut-ins.

The interviews with drivers of vehicles in surrounding traffic did not reveal any strong need for external communication from trucks driving close together today. During the workshop the overtaking scenario was highlighted from car-drivers as one potential scenario that may cause problem, especially in 2+1 roads. The elicited needs mainly concern the movement patterns and properties of vehicles, e.g. speed, direction, gaps and length of the platoon.

Telephone interviews with IVECO and DAF (2) indicate that other traffic interfered with the platoon approximately 10-20 times per day. However, they confirm that the system, that was running in adaptive cruise control, appropriately detects the vehicles that interfere and automatically adapts the safety distance accordingly. Another finding from the interview with IVECO is that their impression is that signaling will not affect the behavior of the other traffic – their impression is that all road users take responsibility of their own driving and if they believe there is room between two trucks they will use it if necessary.

The meeting with Peloton (3) was held at their facility in Mountain View, California. Peloton want to commercialize truck platooning, their investors are among others e.g. Volvo Trucks, MAC, and UPS, and they want to find an efficient solution for their service and seek to clear the obstacles to commercialization. Peloton confirms some of the statistics regarding frequency of cut-ins found from ETPC. Their tests are made in Texas north of Houston. They are interested in the outcome of this project and stressed the importance of grounding any recommendation in scientific evidence before publishing advice whether external signaling is needed or not.

According to Richard Bishop (4), the law enforcement has brought up the need to see if trucks are platoon enabled since it will be illegal to drive at this short a distance, time gaps less than 1s, without the platooning assistive technology. However, they do not see a specific need for external signaling, it could also be solved with V2V communication. The discussions in the US regarding interaction between platoons and surrounding traffic in general and external signaling in particular are not seen as the most urgent issue. Due to the possible problems at short on- and off-ramps, Bishop believes that the first generation of platoons will be two

trucks only. He also points out that the signaling needs to be placed on the tractor also in the US since the trailers switch around. Bishop also noticed a debate whether dynamic indicators would lead to behaviors where the platoon is challenged by persons who wish to "play with the system" to see what happens. However, he believes that this kind of interferences will fade over time. An opinion which is based on testing of other autonomous technologies in real world traffic. Starting in late 2017 the state of Florida will perform a long-term study on platooning in real traffic where also interactions with surrounding traffic will be studied.

## 5.2 What are the communication needs of drivers in other vehicles?

To identify the needs of other road users the following activities were performed:

1. Group interview with regular car drivers (at the same occasion as group interview as with AB Volvo) (number of participants = 4)
2. Telephone interviews with car drivers that annually drive long distances (n=3)
3. Telephone interviews with Swedish truck drivers (n=6)

The group interview (1) confirmed the use cases found in Section 5.1 were relevant also for this user-group. The main concern was about overtaking long vehicles (or in this case a platoon of vehicles).

Telephone interviews with car drivers (2) indicate that interaction with trucks today is a minor problem on Swedish roads. Some of them however avoid staying in the vicinity of trucks and keep a distance or overtake trucks as soon as it is possible. Not everyone understands that driving close together may be done to save fuel.

The interviews with regular truck drivers (3) indicate that Swedish truck drivers are very concerned with safety. They generally stress the importance of driving carefully and keeping a safety distance to other traffic. Occasionally they drive behind other trucks and since they keep a long safety distance there is often other traffic cutting in, both other trucks and cars. With the current safety distance they say that there are interferences regularly, and according to the interviews we interpret this as about 10 times per day.

The interviews with drivers in surrounding traffic did not reveal a strong need for external communication from trucks driving close together today. During the workshop the overtaking scenario was highlighted from car-drivers as one potential scenario that may cause problems, especially in 2+1 roads. However, without having real life experience of a long platoon in one of the critical scenarios identified, it can be difficult to imagine what it would be like, making it difficult to assess the impact of perceived future needs.

## 5.3 How should trucks in the platoon interact with surrounding traffic?

The interviews indicate a number of scenarios where the platoons could use external signaling or V2V communication to share its intention with the surrounding traffic.

In particular on- and off-ramps were scenarios where other vehicles often interfered with trucks e.g. while they drive close to each other using ACC. Discussions about if the platoon should be resolved in busy locations, or e.g. if there is a road-work ahead causing many vehicles to change lane, and presumably interfere with the platoon. A fourth scenario is the possible issue if e.g. an overtaking vehicle should be given the information that he/she is overtaking a platoon of vehicles. How trucks should interact with surrounding traffic depends on the actual scenario. In some cases there is an overtaking vehicle that, if the communication is only on the tractor, will see that they are overtaking a platoon somewhat late. At an on-ramp there may also be a problem for an on-coming vehicle if it is not capable of detecting

that trucks are platooning and it forces itself in between the trucks to make a cut-in. One issue with external light communication is that it may be difficult to detect in daylight.

The best platoon-traffic interaction principle (e.g. stay together, or dissolve whole or part of the platoon) for different situations is however hard to determine based on the available data since it is context dependent and will change due to e.g. number of vehicles in the platoon, distance between vehicles, infrastructure and surrounding traffic. We can however conclude that it would be beneficial for the platoon to have some inherent flexibility to handle upcoming traffic situations in an effective way. Such flexibility requires means for communication and coordination between platoon companions.

#### **5.4 What barriers may exist in a future implementation of external signaling?**

A barrier to implementing external signaling on the trailer is the switch of trailers between haulers. It will be unclear who should pay for the extra cost for implementation and maintenance of the signaling system on the trailers. The possibility of using existing positioning lights should be explored. Another question is how to perform the calculation of if the potential benefit of reducing cut-ins will warrant the implementation cost. Here, the estimation model presented in Section 5.6 may provide some guidance. It is also worth considering the value of providing information to the surrounding traffic in terms of their perceived safety and comfort when interacting with truck platoons. How to perform the transformation of perceived safety and comfort to a value comparable to loss or gain of fuel savings is still an open question.

Barriers that may exist for future implementation of external signaling that has been identified as a possible threat is that trailers are constantly rotating between different tractors. This may require that more trailers than tractors need to be equipped with communication devices. However, the main question of whether communication is needed at all still remains.

#### **5.5 What methods and use-cases can be used for future evaluation of external signaling?**

To further understand the external signaling and the potential effects it can bring, simulation tests should be made and followed up by field tests. One of the main questions is what effect, if any, external signaling may provide. From a safety perspective, we learned from interviews with truck drivers that they keep a safe distance and any interference is handled by the automation in the vehicles. The main idea with platooning is the fuel saving effect, and in the future also labor when trucks may be driven without any driver at all, and in addition, when there is no driver there is no need for a cabin and thus, the truck can potentially take more goods.

In this project, we used animated gif pictures to give inspiration to the interviewees. One example can be found on: <https://youtu.be/hTJtKUvympl>, more examples can be retrieved by contacting the authors. To further elaborate on any possible design of external signaling it is essential to receive the drivers (both truck drivers and drivers on the surrounding vehicle) feedback. One of the major challenges is that platooning is not widely used today and therefore a realistic use-case is necessary for future evaluations. To meet the reality of the industry it may be necessary to consider external signaling on tractors only. The fact that tractors switch trailers constantly makes it challenging (if not impossible) to require external signaling on trailers.

To make efficient evaluation of the effects of external signaling, simulation is our suggestion due to two main reasons: First of all there are very few places that truck platooning takes place today and second, the cost of developing and installing a system may be high in this initial phase. At Halmstad University, research about how to couple the driving simulator at VTI and a traffic simulator (SUMO) that generate traffic as well as platooning vehicles is performed within the VICTIg project. The framework is ready for use and enables a manual controlled vehicle to take any role within the simulation. It allows us to investigate the experience from both truck platoon drivers and car drivers.

The simulator is described in [1] and explains how the controller adjusts the inter-vehicular distance between the trucks in a multi-vendor constellation is controlled and handled in a safe way when manually driven cars interfere with the platoon. Extending the above simulation to focus on the user experience could be a next step to evaluate the effect on external signaling. The simulation study could be followed up by tests in real traffic and a field operational study to evaluate the long term effects of any external signaling functionality. Simulations studies may also include how surrounding traffic adapts to the behavior of truck platoons. The evaluation criteria could concentrate on learnability e.g. how fast will regular traffic adopt to platoons? Another criteria for evaluation could be the fidelity of the means of communication, our aim is to use as little (or as low complexity) as possible and still being able to convey the desired message. We also believe that if external signaling is implemented in the future it should signal the vehicles' intent rather than giving explicit invites to, for example where to cut-in. This principle is based on our previous research in the area of interaction between autonomous cars and other road users [4,5].

One way to evaluate the potential impact of external signaling is for example simulation, where a driver simulator could be used to evaluate both the perception of the car drivers and of the truck drivers. A number of realistic lighting schemes are developed and have been presented during meetings and workshops with the aim to ease understanding of the concept. These may also be subject to evaluation in simulator studies. Another way is to study behavior using naturalistic data collection methods during larger demonstrator projects.

### **5.6 How does disruption of platoons affect fuel saving?**

Reducing fuel consumption is one of the major benefits of platooning. While introducing platooning in mixed traffic there is a risk that surrounding traffic interfere with the platoon and that the potential fuel saving is lost. In this project we developed a model that is used to estimate the potential fuel loss due to cut-ins in platoons. The proposed model is presented in Appendix A.

With the trucks driving in a platoon using ACC in Sweden the interview data indicate that there are approximately 3 cut-ins/100 km. This causes a loss of 0.1 liter/100km in the fuel saving. On European roads the number of cut-ins were estimated by the drivers to between 10 and 20 cut-ins/100km. Due to the higher traffic density every cut-in is also estimated to last longer resulting in a loss of fuel saving of approximately 0.6 liter/100km. The estimations made by the drivers are based on experiences from using ACC where the distance is approximately 1.5 s.

The results are based on a small number of interviews meaning that no general conclusions can be drawn regarding the effect of cut-ins on fuel saving. However, the model can be used to make estimations when more reliable naturalistic datasets are available.

Nevertheless, in a report from US Department of Transportation [3], based on naturalistic data of following distance of trucks, it is concluded that in regular highway traffic there are extremely few cut-ins between trucks with a following distance of  $< 30$  m (1.5 s at 80 km/h).

We have found that there are large regional behavioral differences on how traffic behaves. In naturalistic data from the US, there are no cut-ins if the distance between the trucks is  $< 30$  m. In Europe, the data collected from ETPC indicate that there is one cut-in every 15 km on highways in the Netherlands and Belgium.

## 6 Discussion

The method that was used in the project is highly subjective, nevertheless, the perception of the drivers from ETPC are important for determining the behavior of trucks driving in platoons – and to give an indication of how other drivers interact with the platoons. The subjective data does also correspond to the quantitative data stored from Volvo during ETPC. On the other hand, the data from Europe does not completely correspond to the data observed in the US [3].

Improved fuel saving in platoons due to reduced number of cut-ins is possible. However, driver behavior varies between different countries and regions and so will the fuel savings. It is however clear that a cut-in causes a loss of fuel saving. In the conservative example 0.5 L less diesel was saved daily per day and truck.

A question that emerges is how road user behavior will adapt as truck platoons become more common. For example (as found in the US survey [3]) will drivers still avoid cut-ins below 30 m following distance on highways, or will these figures change over time? Today, the  $< 30$  m distance is in itself a signal that seems to deter other vehicles from interfering with a platoon.

Another question is how road user behavior will change when/if platoons become longer than 2-3 vehicles. It is unknown if cut-in behavior may increase in certain situations. Surrounding traffic will need to interfere at e.g. on- and off-ramps when it is blocked from access by a platoon. In the future, the public's behavior may adapt while being more used to interacting with platoons, other behavior patterns may emerge as compared with today.

## 7 Conclusions

The general conclusion from the studies made in this project is that in Sweden, and during traffic conditions similar to today's traffic, there is no urgent need to deploy external signaling for future platoons with two trucks, neither if they are driving in ACC-mode with 1 s headway or using V2V with 0.5 s headway, since the traffic density in most cases will allow for other traffic to interact smoothly with platoons. In Europe the situation is different, because the traffic density is much higher. However, based on the current study, we can not conclude that external signaling is needed in Europe. The subjective data collected in the project support that cut-ins can be reduced to close to zero with a vehicle distance of 0.5 s headway.

## 8 Further research

For platoons with more than two vehicles the need is however uncertain and it is difficult to predict the impact that very long platoons have on surrounding traffic. Thus we suggest further studies to study the interaction between long platoons and surrounding traffic at the scenarios identified as critical in the project (on-ramp, off-ramp, overtaking and lane change). In the first stage simulations, where a driving simulator may be used to mimic the experience of driving in either the platoon or in a car that interacts with the platoon, can be made. The simulations may also to some extent capture the needs of any additional technologies. In particular the simulations would give valuable input on such technology that is yet to be developed and tested. A drawback with simulations is that they may have difficulties to capture subjective feeling of safety and control. This leads us to the second stage where naturalistic data should be saved to study the behavior in Europe in a similar fashion as in the US [3], to further clarify the European arena for platooning, interaction with surrounding traffic and possible need for external signaling.

## 9 Goal fulfilment

The overall research questions were studied in four work packages. Each WP contributed to answer the overall research questions of the project.

- Map and follow up experiences from previous platooning projects and activities (with regards to external signaling)

Experiences from the European Truck Platooning Challenge ([2], workshops and interviews), i-Game (participation), Scania Transport Lab platooning (workshops and interviews), Peloton (interviews), and the US naturalistic study on truck following behavior [3] has been incorporated in the project as described in the report.

- Obtain the needs for communication between platoons and surrounding traffic

Needs were obtained by means of two workshops at Scania and AB Volvo and 11 interviews with other truck- and car drivers. Meetings with Peloton and Richard Bishop provided valuable input to the needs on both technical and societal perspectives.

- Define use cases and criteria for future evaluation of external signaling

Four relevant scenarios were identified for future evaluation of external signaling: on-ramp, off-ramp, overtaking and lane change. The scenarios represent situations where cut-ins often occur.

How evaluation can be done in a driver and traffic simulator has been described. Evaluation of learning effects, e.g. how long time it takes to get used to trucks that drive with short inter-vehicular distance (e.g. 10 m) may be performed.

- Judge the fuel saving benefit when avoiding break-up of the platoon

A model for calculating the potential fuel loss reduction due to cut-ins has been developed (Appendix A). In the presented scenario and with the assumptions made, the model estimates a benefit of fuel loss reduction due to avoided cut-ins by at least 0.5 L diesel per day per truck.

## 10 Dissemination

### 10.1 Dissemination of knowledge and results

Project results have been used as input to other projects at RISE Viktoria, for example the Drive Sweden project "Methods and Metrics for Evaluation of an Automated Transport System", where analysis of platooning has been applied as a use-case.

The project has also inspired future continuation of applications in the area of external signaling between road users (i.e. the AVIP-project [4, 5]).

The project was a door-opener to contact several of the European partners in ETPC, where we now have good contacts. We also discussed the project with Peloton and Richard Bishop, who appreciated the work and were interested in the outcomes.

The project has a web-page on: <https://www.viktoria.se/projects/kommunikationsbehov-vid-interaktion-mellan-lastbilar-och-omgivande-trafik>.

### 10.2 Publications

Fuel saving paper – to be submitted to TRB platooning session (see draft version of the paper in Appendix A).

## 11 Project partners

Participating partners are RISE Viktoria, AB Volvo and Scania. See Table 2 for an overview of the partners and the contact persons within each organization. The project was led by Cristofer Englund at RISE Viktoria.

*Table 2. Overview of project partners and their corresponding contact person.*

Part	Contact person	E-mail
AB Volvo	Anders Berger	Anders.berger@volvo.com
Scania	Jan Dellrud	Jan.dellrud@scania.com
RISE Viktoria	Cristofer Englund	Cristofer.englund@ri.se

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## Appendix A

Draft paper: Modeling loss of fuel reduction due to cut-ins in truck platoons. To be submitted to TRB.

# Modeling loss of fuel reduction due to cut-ins in truck platoons

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## Abstract

Reducing fuel consumption is one of the major benefits of platooning. While introducing platooning in mixed traffic, surrounding traffic will interfere with the platoon and there is a risk that the fuel saving is lost. In this work, a method to estimate potential fuel loss due to cut-ins in platoons is presented. Based on interviews with truck drivers with experience from platooning, and naturalistic data from previous research we estimate the potential loss of fuel saving due to cut-ins and compare two scenarios of different amount of traffic. The results show that loss of fuel saving is noticeable and globally it would make a significant impact on fuel consumption.

## 1 Introduction

Platooning is a technology that allows vehicles to drive with short inter-vehicular distance to reduce aerodynamic drag and thus save fuel [LMJ14]. As a consequence, when the distance between vehicles decrease, more vehicles can be accommodated on the roads leading to improved road utilization. Platooning is enabled by vehicle automation and vehicle-to-vehicle (V2V) communication. These technologies allow vehicles to collaborate on a short time scale [ALJE15], and thus, the control systems of the vehicles will be able to react simultaneously to maintain safety, since they are aware of each others' actions and intentions.

Platooning for fuel saving is previously studied in several projects, see [BSC<sup>+</sup>12] for an overview of platooning projects. The fuel saving for such systems is significant and in e.g. [Tsu13] fuel savings of more than 20 % for some situations is reported. In this paper we investigate the potential loss of fuel savings due to interference from surrounding traffic and in particular cut-ins. The main reason for cut ins are vehicles that are either joining a highway from an on-ramp or vehicles that suddenly need to exit the highway. Other scenarios include merging due to an upcoming roadwork or courtesy maneuvers from overtaking vehicles to let fast upcoming vehicles from behind to pass.

### 1.1 Background on fuel consumption

This section gives an introduction to how fuel consumption can be estimated for platooning trucks.

Fuel consumption for vehicles is proportional to the energy extracted from the fuel:

$$m_{fuel} = \frac{E_{fuel}}{c_p^{diesel}} \quad (1)$$

where  $E_{fuel}$  is the total energy stored in the fuel and  $c_p^{diesel}$  is the specific energy density of diesel (for diesel-operated vehicles).

To compute the total fuel energy, considerations needs to be taken on how this energy is used. More than 50% is dissipated by the engine, encoded into the engine efficiency  $\eta$  (for modern diesel engines engine efficiency is about 35-45%). Other major energy drains are air resistance and rolling resistance. Fuel energy is also used to overcome gravity on the uphill resulting in higher potential energy. On the downhill this potential energy is converted back to kinetic energy (vehicle speed). However, to stay within speed limits, excess kinetic energy is irreversibly converted into waste heat by the friction disc brakes. In addition, the gear box adds extra friction.

For a general introduction to vehicle modeling and fuel consumption modeling, see books by Guzella (2013), [GS13] (with a very concise introduction to fuel consumption in Chapter 2), Eriksen (2014) [EN14], Crolla (2009), [Cro09] and Crolla (2012) [CM12].

One way to model fuel consumption is by considering instantaneous total tank-to-wheel fuel efficiency over the driving mission. Integration can be performed either over time or over distance:

$$E_{fuel} = \int_{t_1}^{t_2} P_{fuel} dt \quad (2)$$

where  $P_{fuel} = \frac{dE_{fuel}}{dt}$  is power and  $F_{fuel} = \frac{dE_{fuel}}{dx}$  is force.

Vehicle dynamics in the time domain can be written as follows:

$$m\dot{v} = F_{wheel} - F_{air} - F_{roll} - F_g \quad (3)$$

where:

- $m$  is the equivalent mass that includes the actual vehicle mass and terms reflecting inertia of rotational components,
- $v$  is the longitudinal speed,
- $F_{wheel}$  is the total wheel force,
- $F_{air} = \frac{1}{2}\rho_a c_d A_f v^2$  is the aerodynamic drag,
  - $\rho_a$  is the air density,
  - $c_d$  is the drag coefficient,
  - $A_f$  is the reference area,
- $F_{roll} = mgc_r \cos \alpha$  is the rolling resistance,
- $F_g = mg \sin \alpha$  is the gravitational force,
- $\alpha$  is the slope (gradient) of the road.

Staying within the space-domain, the left-hand side of the equation (3) can be rewritten as following:

$$m \frac{dv}{dt} = m \frac{dx}{dt} \frac{dv}{dx} = mv \frac{dv}{dx} = \frac{d}{dx} \left( \frac{mv^2}{2} \right) = \frac{dE}{dx} \quad (4)$$

where  $E = \frac{mv^2}{2}$  is the kinetic energy.

Then, assuming that all force from the engine  $F_{eng} = \eta \cdot F_{fuel}$  goes into the wheels together with the braking force  $F_{brk}$  (i.e.  $F_{wheel} = F_{eng} - F_{brk}$ ), the vehicle dynamics equation (3) can be rewritten as follows:

$$\frac{dE}{dx} = F_{eng} - F_{brk} - b_{air} \cdot E - F_{roll} - F_g \quad (5)$$

where  $b_{air} = \frac{\rho_a c_d A_f}{m}$ .

Then the fuel consumption is

$$m_{fuel} = \frac{1}{c_p^{diesel}} \int_{x_1}^{x_2} \frac{1}{\eta(x)} F_{eng}(x) dx \quad (6)$$

Substituting the expression for  $F_{eng}$ , we obtain the following:

$$m_{fuel} = \frac{1}{c_p^{diesel}} \int_{x_1}^{x_2} \frac{1}{\eta} \left( \frac{dE}{dx} + F_{brk} + F_{air} + F_{roll} + F_g \right) dx \quad (7)$$

In the time domain, fuel consumption becomes

$$m_{fuel} = \frac{1}{c_p^{diesel}} \int_{t_1}^{t_2} \frac{1}{\eta} \left( \frac{dE}{dx} + F_{brk} + F_{air} + F_{roll} + F_g \right) v dt \quad (8)$$

where  $v = \frac{dx}{dt}$  is the speed.

## 1.2 Observations on platoon fuel-saving for vehicles of different mass

In the fuel consumption formula both rolling resistance and gravity/braking depend on vehicle mass, while air resistance is independent of mass. Platooning reduces only air resistance, while rolling resistance remains unaffected. Thus the relative fuel consumption reduction will be much larger for light vehicle where air resistance plays a larger role. Conversely, for heavy vehicles, where fuel consumption is dominated by the rolling resistance, gravity and braking, the relative fuel consumption would be lower.

## 1.3 Platooning on non-flat road

Previous work on fuel savings was published in [Ala14]. In this work there is an example of a platoon that arrives at an uphill where the first vehicle in the platoon slows down due to a weak engine (normal behavior). However, the second vehicle has to brake, not to crash into the first one. Such braking dissipates energy and should not occur. Braking can be avoided by increasing the gap when the platoon is approaching an uphill. Such optimization approaches are presented in e.g. [MEN16] and [HL16]. Questions that arise while opening the gaps between trucks in a platoon are: ‘‘How much does the air resistance increase?’’ and ‘‘Does the increased gap invite to additional cut-ins?’’.

## 2 Cut-in

At a cut-in, air resistance increases. Even if a vehicle cutting-in is a truck with a shape similar to the original preceding vehicle, due to the absence of the V2V platoon communication, the safety distance have to be increased compared to while in the platoon operation. Moreover, if the shape of the vehicle cutting-in is not platooning-optimized, like of a passenger car, the air resistance is increased even further. Also, the truck behind the cutting-in vehicle will increase its distance to its platooning companion even further.

The literature provides fuel consumption reduction figures for a homogeneous platoon with varying gap. Thus we will assume that cutting-in vehicles are similar in shape to the platoon vehicles, and that the air resistance increase is only due to the increased gap.

There are two main types of figures related to fuel consumption reduction in platoons: one type shows reduction of the drag coefficient for platooning vehicles, usually acquired using Computation Fluid Dynamics (CFD) or in a wind tunnel; the second type is the measured fuel consumption for the complete set of vehicles, usually measured on a test track [BF00]. A general reference for aerodynamics of vehicles is the book *Aerodynamics of Road Vehicles* published by SAE [Sch15]. Field tests on real roads and real traffic are generally challenging for estimating fuel consumption, as the traffic situations varies, as well as pavement properties, weather, wind direction etc. See Fig. 1 for typical air drag coefficient reduction depending on position in the platoon and the headway distance.

### 2.1 Example

Let us say a cut-in remove all fuel consumption reduction. At 10 meters inter-vehicular distance, the air drag reduction is about 40%. Assuming that air resistance stands for approximately 1/3 of the fuel consumption for a 40-ton vehicle, and fuel consumption is about 30 L/100 km for an ordinary topographic profile and that air resistance consumes about 10 L/100 km. Driving at 10 m distance saves 4 L/100 km. This is consistent with 10-15% total fuel saving for a complete vehicle.

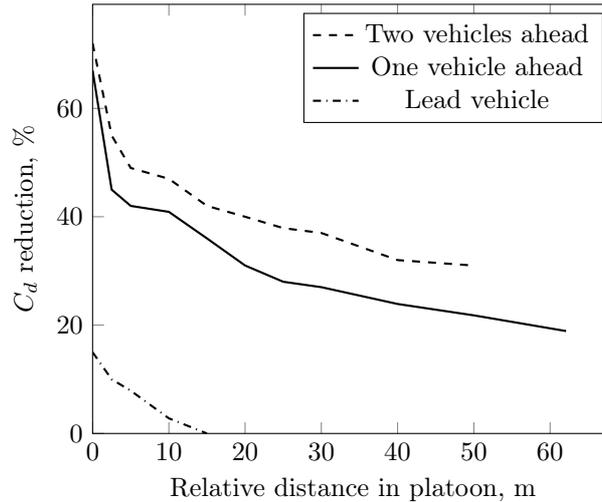


Fig. 1: Reduction of air drag coefficient  $C_d$  depending on the position in the platoon and headway distance. Adapted from [AJ10, BF00, Sch15].

Assuming one cut-in lasts  $t = 45$  seconds (s), it corresponds to the distance of  $d = 1$  km at the speed of  $v = 80$  km/h.

Then cut-ins introduce the following loss into the platooning fuel consumption reduction, in L/100 km:

$$m_{lost} = \gamma_{platoon} \cdot \gamma_{air} \cdot m_{fuel} \cdot \frac{n_{cut} \cdot d_{cut}}{100 \text{ km}} \quad (9)$$

where

- $\gamma_{platoon}$  is the air drag reduction in percent, e.g. 40% at a gap of 10 m,
- $\gamma_{air}$  is the proportion of fuel that is used to overcome air resistance, e.g. 1/3 for a 40-ton truck,
- $m_{fuel}$  is the total fuel consumption, in liters per 100 km, e.g. ca 30-40 liter per 100 km for a 40-ton truck,
- $n_{cut}$  is the number of cut-ins per 100 km,
- $d_{cut} = v \cdot t_{cut}$  is the average length of a cut-in,
- $v$  is the platoon speed,
- $t_{cut}$  is the average duration of a cut-in.

## 2.2 Note on braking

If a cut-in is sudden, the platooning vehicle might be forced to brake heavily. For such braking, a mechanical friction brake might be used, which irreversibly dissipates energy. This might be avoided through using recuperating brakes of hybrid or fully-electric vehicles. If only a soft braking is required, it can be achieved instead by engine braking or even coasting, which should minimize parasitic energy dissipation.

## 2.3 Frequency of cut-ins

To make qualified calculations on the effect that cut-ins have on fuel consumption interviews were made with regular truck drivers as well as truck drivers with experience from platooning (European Truck Platooning Challenge). Eight interviews with truck drivers from Sweden and two from IVECO and DAF were made. In addition, a group of six truck drivers from the Transport Lab at Scania and four truck drivers from Volvo Trucks were interviewed. Moreover, six car drivers were interviewed to obtain the opinion from surrounding traffic.

### 3 Estimating the effect

From the interviews with truck drivers that use adaptive cruise control with time headway 2 s (approximately 45 m) we estimate that there are approximately 3 cut-ins/100 km on a regular Swedish highway, each cut-in lasts for about 45 s. This corresponds to a fuel loss of 0.1 L/100 km. Assuming 500 km of driving per day, the total loss is about 0.5 L per day. In 2014, Volvo AB sold 203,124 trucks <sup>1</sup>. Assuming 250 working days a year, gives about 25,000,000 L in lost fuel saving per year for a fleet comparable to the one sold by Volvo AB in a year. Not all vehicles will drive in platoons, and platoon leaders typically save less fuel than the followers, indicating that this figure is too high.

In the central European countries, e.g. Germany, the Netherlands, the number of cut-ins is higher due to the generally higher traffic density on the roads. Interview results from European drivers indicate about 10 cut-ins/100 km. This figure is also in line with [NLYN17], who found 4974 cut-ins in 44000 km of naturalistic driving data. Given the higher traffic density we assume it is more difficult to leave the pocket between two trucks entailing that each cut-in lasts for about 90 s, we obtain 0.6 L/100 km. Assuming 500 km of driving per day, the total loss is about 3 L per day.

In the study from US Department of Transportation [NLYN17] it is concluded that for headway distances  $< 30$  m ( $< 1.5$  s) no cut-ins were observed when following another truck and very few cut-ins were observed when following a light vehicle. In interviews with Swedish truck drivers in the ETPC, they report that when driving with a 22 m gap (1.0 s at 80 km/h) Swedish passenger cars avoid going in-between the trucks. However, while driving in the Netherlands and Belgium cut-ins were occurring despite the short distance. Clearly, there are differences between countries/regions to when, where and how cut-ins occur. Whether the differences in behavior are due to contextual (traffic density, infrastructure design) or cultural factors remain unclear and is a subject for further research.

### 4 Discussion

The model to assess fuel saving reductions is based on the physical properties of a platooning scenario. To use the model several assumptions have to be made. The assumptions made in our example are mainly taken from subjective assessments made by experienced drivers and empirical data from a small number of tests in real traffic. They give an estimate, but are not as precise as one could wish for, indicating a need for further studies to collect data on real traffic behavior. Even though the figures given by the example in section 2.1 only give very rough impression of the magnitude of possible future losses of fuel savings, the model can be valuable for use in future studies of cut-in behavior when additional data of high quality has been collected.

With the conservative estimate on the number of cut-ins and the duration of the interference, there is still a potential to increase fuel savings for trucks - if they are allowed to drive in a platoon without being disturbed by surrounding traffic.

### 5 Conclusion

A method to estimate potential fuel loss due to cut-ins in platoons is presented. General theory for vehicle and fuel consumption modeling is used to model the fuel consumption for the vehicles in the platoon. To estimate the potential fuel saving loss due to cut-ins, results from interviews with truck drivers with experience from platooning in Europe and naturalistic data from the US was used. The results indicate that there is a potential loss of fuel saving of up to 3 L per 500 km driving, while surrounding traffic are interfering with a platoon. Particularly in high density traffic with long distance ( $>2$  s time gap) between the trucks in the platoon.

### Acknowledgement

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