Evaluation approach for a combined implementation of Day 1 C-ITS and Truck Platooning – v.1.0

C-Roads-Italy Platform

Ex Ante Evaluation

Index

Title:

Evaluation approach for a combined implementation of Day 1 C-ITS and Truck Platooning (Ex-Ante Evaluation)

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1 Introduction

This Ex-Ante evaluation has been carried out as one of the activities of C-Roads Italy, in order to assess the expected impacts deriving from a jointed implementation of both C-ITS day 1 Services and the Truck Platooning system on the basis of the currently available bibliography. This activity is aimed to a first definition of these impacts, mainly in the four impact areas defined in Fot-net 2017 [114] and currently used also within the activities of C-Roads Europe. First, to achieve this objective, in Chapter 2 the available bibliography concerning the Truck Platooning system and the possible levels of automation achievable is analyzed with a particular focus on the impacts that the system alone could entail on the European road network. Therefore, through the paragraphs of Chapter 2, the system is characterized without referring to a specific OEM's product and the most likely implementation logics in the short and medium term is drawn. Thus, in 2.8, an overview of the expected impacts found in literature is provided, pointing out what are the most acknowledged results and which ones are still a research subject, instead. Then, in Chapter 3, how to evaluate the system's impact on Traffic Efficiency, Environment, Safety and User Acceptance is studied, mainly on the basis of research and sub-research questions. The objective of Chapter 3 is to provide the evaluators across Europe with the tools to design both field tests and modeling works in a coherent and similar way, without losing a necessary grade of freedom needed to account for the local specificities and the differences between different Truck Platooning solutions. Besides, it should be noted how the bibliography concerning the jointed implementation of the Truck Platooning system and C-ITS Day 1 Services is still scarce or lacking, mainly because both these innovative systems are currently being developed and first experiments on roads are being carried out recently. For this reason, in Chapter 4, the same approach is applied on the jointed implementation of the Truck Platooning system with each Use Case of the C-ITS Day Services judged relevant on the basis of the bibliographical review and of the C-Roads documents produced by the Working Group 2 - Taskforce 2. Both Chapter 3 and Chapter 4 accomplish the objective of an Ex-Ante evaluation, identifying the impacts, but go a little further, highlighting the tools needed to assess each one of them, the most relevant scenarios, the data judged useful and suggestion on the indicators that should be collected from field tests or obtained from modeling works. Thus, the foundation for the future evaluation activities of C-Roads Italy is laid.

It is important to highlight how both Chapter 3 and Chapter 4 contain suggestion and best practices, therefore nothing contained there can be considered mandatory. Moreover, both these chapters are based on the bibliographical review and aren't referred explicitly to the field tests and future activities that will be carried out within C-Roads Italy. These chapters are born as indicative frameworks that can and will be used to optimally design the evaluation activities of C-Roads Italy but don't reflect perfectly the activities themselves. For example, even if in this Ex-Ante Traffic Efficiency, Safety, Environment and User Acceptance are analyzed for each Use Case in its joint implementation with the Truck Platooning system, it can't be said that the field tests that will be carried out within C-Roads Italy will evaluate each one of them for each Use Case. This Ex-Ante has been conceived as a contribution for the work of current and future evaluators across all Europe for every activity linked to the Truck Platooning system and the C-ITS Day 1 Services, not just the ones that will be accomplished within C-Roads Italy in the next years.

2 Truck Platooning – Bibliographical Review

2.1 System overview

Truck Platooning is a set of heavy vehicles that, through the use of the Cooperative Adaptive Cruise Control (CACC), can *speak* to each other. This communication allows driving with strongly reduced headways, which can be achieved because the vehicle in front broadcasts information about its driving regime to the following ones. Information sent this way include accelerations and decelerations, location, sudden braking and target velocity; by knowing those parameters, the cruise control on each of the following vehicles can adapt their driving so that no collision should occur even when the distance is reduced. With this technology installed on heavy vehicles becomes possible to entrust the longitudinal control to the automation, leaving the drivers to perform the lateral control or, even, to simply monitor the system. That happens when also the lateral control is entrusted to technological equipment like the lane centering system or the lane keeping system, this kind of configuration entails higher levels of automation but also higher expected benefits in significant fields. Therefore, truck platooning can fall in the levels of automation L2 or L3 defined by the NHTSA classification [61]. In the short term it is reasonably the former one who is going to be deployed on public roads, this is due to both technological and legal barriers. For this reason, in this report, the impacts of L2 truck platooning are going to be analyzed (unless clearly stated otherwise).

> Level 2 “involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. Vehicles at this level of automation can utilize shared authority when the driver cedes active primary control in certain limited driving situations. The driver is still responsible for monitoring the roadway and safe operation and is expected to be available for control at all times and on short notice” [61].

In [25] an automated Truck Platooning L2 is considered, and is clearly stated that merging, forming and dissolving the platoon are function entrusted to the system. In the same work, the pilot “Real-life cases Truck Platooning” [14,15] is mentioned, as follow up demonstration of the European Truck Platooning Challenge.

When the longitudinal control is taken away from the driver, it is possible to bypass human reaction times and the resulting meters needed in the kept headway to ensure a safe braking maneuver. The CACC, by receiving information about accelerations and decelerations of the preceding vehicles, knows when to brake almost in the same instant the brake pedal is pressed in one of the vehicles ahead. In that way the headway must be wide enough to let the braking happen but can be shorter because the meters the drivers need to understand the situation and act accordingly can be neglected.

Closer trucks involve economic, environmental and social benefits as will be explained later in this Ex-Ante evaluation. Besides, the use of the CACC leads to a more stable and regular traffic flow. This happens because the common disturbances generated when a vehicle brakes are not propagated upstream, the WIFI connection allows the system to adjust the vehicle's driving and make the following vehicles absorb the perturbation that can create shockwaves, accelerating and decelerating almost as one. This has a positive impact both when the leading vehicle brakes in a sudden way, and when the perturbation arises outside the platoon. If that is the case, even when the platoon itself is victim of external events, it still can help preventing or delaying traffic jams thanks to the more regular driving assured by the CACC.

> "Information about preceding and following vehicle is grabbed by the inter-vehicle communication system that allows previewing information from vehicles further. As compared with the case without inter-vehicle communication, the upstream vehicles do not have to brake as severely when a downstream vehicle brakes which, results that an anticipatory braking action." [91]

To cite [95]: "Simple analytical considerations, based on the flow theory, prove that, even just the nullification of action and reaction times by the means of automation, involves great benefits in the road outflow".
Information between vehicles are passed by Dedicated Short Range Communications (DSRC), which use a WIFI connection that follows the ETSI standard ITS-G5 on a 5.9 GHz band and a dedicated IEEE 802.11p. It is important to note that in the near future it's likely that this kind of communication will be exploitable by means of 5G hybrid systems and cellular networks. This connection between vehicles in a platoon is a type of V2V (vehicle to vehicle) communication, similar to the ones used in the definitions of the C-ITS Day 1 and specified in the ETSI documents.
Each of the trucks in a platoon can be equipped with other driving support systems like Forward Collision Warning, Lane Change Assist, Here I Am and Traffic Jam Assist, just to name a few. All those components are currently on the market and their cost of purchase and installation has a lower impact on a heavy truck than on a car. This is one of the reasons truck platooning can be a reality sooner than other partially automated systems and be the first transport system to exploit the benefits inherent in the C-ITS deployment.

> "CV [Connected Vehicle] is more significant for heavy commercial vehicles than for light vehicles because the organized nature of heavy vehicle operations benefits more from connectivity. Fleets have an important role to play in deploying the technology, engaging with smart cities and communities, establishing connected corridors and precincts, and

developing new accommodations for heavy vehicles, including signal priority and truck parking." (Evolution of Technology for Commercial Vehicle Safety - Sweatman P. 2017)

"The electronic equipment needed to automate a truck should not be very different from equipment needed to automate a passenger car, since its functions are essentially the same. It means that the cost of automated system for an ACT should be almost the same as a passenger car. However, a heavy truck would typically cost much higher than a passenger car. This factor makes the potential economic return from an investment in automation equipment significantly more attractive for a truck than for a passenger car." (Design and Control of Automated Truck Traffic at Motorway Ramps. – Tabibi M. 2004)

It is important to note how the time horizons foreseen by the European Union for both Truck Platooning and C-ITS services are essentially similar: while the deployment of the first Day 1 services is going to happen in 2019, the first truck platoon on European public roads is likely going to drive on 2020. In Italy, within the activity of C-Roads, a joint deployment is planned in the same period.
A recent feasibility study about truck platooning, carried out in the UK, states that "Convoying (where drivers remain 'in control' of the vehicles) could be implemented in the short term (1-2 years) and platooning (where drivers could disengage to a greater extent from the immediate driving task) in the medium term (3-5 years)" [105]. Similar time horizons are hypothesized in [120], projected on the American reality.
An overview of the issues that still hinder the Truck Platooning system from becoming reality on public roads is presented in [112], a work that considers also all the promising aspects that foster the implementation, instead.
Still, currently the spotlight seems to be focused on Truck Platooning. For example, the Truck Platooning system is explicitly mentioned in [126] where is foreseen to be available by 2020.
Currently, technology seems to be way ahead national legislations and social acceptance, the time gap between two heavy vehicles connected by CACC can be as low as 0,5 s and, by 2020, this value is probably going to be 0,3 s [60], still ensuring security standards and performances at least equal to the ones characteristic of manual driving. Time gap is a headway that, depending on the instantaneous speed, represent the Δt needed for the front of the following vehicle to be in the exact same spot where the rear end of the leading vehicle is in $t = 0$. Imposing that kind of headway in the control algorithm guarantees that each vehicle has the same speed and acceleration for each point of the road. In this way a truck is guaranteed to have the right driving regime to pass curves and slopes on the itinerary. Practically time gap is "(…) defined as the inter-vehicle distance divided by the follower vehicle velocity" [90], this spacing policy guarantees string stability as long as the speed of the platooning leader remains constant [19]. String stability is obtained when the response to the changes in speed of the leading vehicle by the following vehicles don't amplify its oscillations

downstream (namely, the following vehicles follow the change in speed of the leading vehicle almost perfectly). String stability can be achieved inside a platoon of CACC-equipped vehicles, not among the overall traffic flow (at least in the short-medium term) but a string stable element has a steadying effect on the overall flow, enhancing Traffic Efficiency for all the road users.

> "By specifying the desired trajectory of the follower vehicle to be a time-delayed version of that of its predecessor with time delay Δt>0, it can be shown that all vehicles in the platoon achieve the same velocity profile in the spatial domain. This is an advantage as the desired velocity profile is typically determined by road properties such as bends and hills, making the delay-based spacing policy well-suited for potentially long platoons." [41]

Road topology should not be overlooked, being able to dissolve a platoon when the different deceleration ratios and gross weights are not evaluated from the control algorithm, as will be analyzed in the following paragraphs. The platooning application needs to address the road topology that influences the performance of the platoon [94]. Practical string stability should consider, also, time lags in sensors and actuators, delays in sensor measurement and signal processing, model mismatches, measurement noises and external disturbances from the environment (such as road and wind) [104].

Another spacing policy often considered in the Truck Platooning field is the constant vehicle spacing: in this configuration the distance between two heavy vehicles is constant and independent from the kept speed values. An important advantage of this control law is that it assures an improved string stability (and, consequently, a major shockwave damping capacity) over the constant time gap policy, besides it is easy to implement in practice [19].

In [19] is also stated, though, how the optimal configuration is the one that allows the headway to dynamically adapt itself to the situation and to the progression of the platoon along the infrastructure:

> "In addition to basic platoon acceleration and deceleration, inter-vehicle distance adjustment is defined for different traffic scenarios and road facilities. For example, large inter-vehicle distances would be required when a platoon approaches ramps to enhance safety for other vehicles. After passing the ramp area, the inter-vehicle distances in platoon can be reduced to enhance air-drag reduction and fuel saving."

A rather similar approach is followed, for example, in [81], where the "functional combination between platooning and traffic-adaptive intersection control" is developed and evaluated or in [89] where the possibility to increase the gap in merging scenarios is explored. In [60] is stated, based on a stakeholder consultation, that "In some cases, the gap distance between vehicles could even be (dynamically) changed to accommodate specific situations such as near bridges or tunnels".

In the near future, trucks will become connected vehicles, able to exchange information with other vehicles (V2V communications), with the infrastructure (V2I communications) or with external servers dedicated to management and coordination of the fleet (communications by Cloud). However, that kind of transformation leave different questions to be answered, like the functional specification and requirements that the connection must have to guarantee an acceptable level of safety. The flow of data must be protected in order to avoid stealing or hacking, the same propriety of those Big Data has still to be defined. The situation across the European countries is described in [42]: Car manufacturers, currently, claim ownership of those while potential service providers hope for at least partial sharing of this ownership. The same study identifies the possible connections between the truck platoon and the rest of the world, addressing the need for those connections to be interoperable (capable to communicate with all kind of vehicles, infrastructures and servers) in order to earn all the possible benefits of Truck Platooning and of cooperative mobility. Other important requirements identified by this work are the *generalized interaction with the vehicle* and *the adequacy to cooperative active safety driving applications*. The former is defined as the capacity of the connection to exchange data with the vehicle’s equipment, the latter represents, instead, the requirement needed about coverage, level of service, message latency and availability.

Usually, the higher the level of automation, the safer the system must be. Truck Platooning is no exception and, in order to be a “fail safe” system, it must rely on a certain redundancy about its information-gathering systems. Because of that, a heavy vehicle intended for platooning relies not only on DSRC for driving, but also on radars, LIDARs, GPS, inertial navigation systems, infrared sensors, lasers and cameras.
It is also worth noticing that the European Union General Safety Regulation 661/2009 mandates Autonomous Emergency Braking and Lane Departure Warning System for vehicles heavier than 8 tons entering the market from 2013 and for all new vehicles entering the market after 2015 [105].
As mentioned before technology is way ahead the initial phase and almost ready for deployment on public roads. Yet, there are other limitations like the legal ones or the ones bound to acceptance, both from the truck drivers and from public opinion. Another important issue is the number of stakeholders involved, each with their interests, just to name the most important ones:

- truck makers
- original equipment manufacturers (OEMs)
- shippers
- truck drivers
- road operators, road authorities
- political decision-makers
- service providers

- insurance agencies

All those actors have a decisive role in the deployment of the system in the next years and must act in a coordinated way, in spite of their often conflicting interests. The truck makers, for example, must adopt interoperable technologies that can communicate with each other, even if they are competitors. Besides, Truck Platooning is a system suited for trans-national and cross border transport services. It is, therefore, beneficial that every country on the main good-oriented roads is inclined to use and support this transport system.

C-Roads aims to tackle the risk of a disjointed implementation of cooperative systems with pronounced differences among nations, with this report and all the future activities planned, C-Roads Italy aims to do the same also for Truck Platooning.

An inadequate communication among stakeholders or a missing coordination activity on the European level can lead to a sub-optimal implementation and a lacking level of service for the end-users of Truck Platooning. Many of the possible benefits of the system in the social, economic and environmental field could be lost due to lack of common validation procedures, safety requirements and guidelines for the design of field tests on public roads. The legal framework of the involved countries must be harmonized in the following field:

- safety distance
- speed limit for the platoon
- gross maximum weight
- addition among European countries of the semi-autonomous driving in the legislation

Some countries are more prepared to face this kind of issues, the Netherlands, for example, established an exemption procedure in national legislation to ease Truck Platooning testing.

On the Italian level is important to define an exemption procedure in order to design field tests on public roads, specifying the performances required to the system tested and the minimum safety standards. It is worth remembering that, during the European Truck Platooning Challenge, one OEM had to require six different exemptions to drive across three German Länder and five countries [24].

> “A next step envisioned was to introduce a set of procedures to the European authorities as a possible future certification standard for automated transport systems” (van Dijke & van Schijndel)

Limiting, in the short term, the deployment of innovative transportation technologies to the most advanced states in these fields, can make the European market of both C-ITS and Truck Platooning ludicrous towards other large markets such as the American or the Asian ones. That situation can easily lead to the imposition of extra-European standards to the Union, which is why it is fundamental to develop a strong and widespread employment among all the countries in Europe.

It should be noted that, at the European level, steps have been made to move in this direction. On December 13, 2016, an amendment to the Vienna Convention on Road Traffic has been implemented. This amendment “allows the transfer of driving tasks to the vehicle itself, provided that the technologies used are in conformity with the United Nations vehicle regulations or can be overridden by the driver […] (Act to Amend Articles 8 and 39 of the Convention on Road Traffic of November 8, 1968)” [92].

Another issue that still has to be tackled before an optimal implementation of Truck Platooning is its relationship with European infrastructures, not designed for a truck platoon and which present some critical points in this regard. A set of trucks, driving really close one another, can be a disturbance for the surrounding traffic in key points like: roundabouts, bridges and ramps, it is also important to note that for really long tunnels the latency of WIFI communications could become a serious issue that has to be considered. Moreover, as stated in [117], Road Operators can be concerned from the risks arising by fires within tunnels, current regulations and technical implementations are, in fact, designed for fires in a single truck, therefore changes are needed to adapt tunnels and make them suitable for Truck Platooning. For bridges there is another potential obstacle to overcome: a reduced headway and a perfect lineup of trucks, possibly supported by the Lane Centering or just by cameras, could greatly increase the load exerted on the infrastructural element. About this issue, recently, spoke Richard Bishop of the Peloton Technology:

> “Recently, Florida DOT shed some light on the issue, noting that for 80,000 pound trucks platooning at spacings of 30 feet or more, only 6 of their 2000 highway bridges could potentially have a problem due to their condition. First generation platooning systems will almost certainly run at gaps higher than 30 feet. But for such bridges or any other infrastructure elements for which state officials have concerns, platooning developers have noted that geo-fencing could be used to de-couple at before encountering these locations.” [93]

Holding the formation of a truck platoon near ramps is a complex issue, so that more than one approach has been proposed to address it and will be dealt with in detail in some of the following paragraphs. Regarding the possible interference of a fairly long platoon in a roundabout and the blockage of approaching branches, there isn’t an adequate bibliography at the present time, this could be because in the short-term Truck Platooning will be deployed only on the main roads and the very rare roundabouts on the route could be avoided with appropriate diversions. In a wider time horizon, however, it is foreseeable that small platoons of trucks will be able to travel on ever larger

portions of the network and the subject of roundabouts will become more relevant. At this stage C-Roads Italy won't valuate the roundabout subject.
A further obstacle that must be overcome is the lack of a solid business case that accounts for different legislations among European countries and progressive automation of Truck Platooning up to L4 [61] in the long run. In the Study on the Deployment of C-ITS in Europe: Final Report [8], wrote from Ricardo Energy&Enviroment is stated as follows:

> "Impact and cost data for vehicles other than passenger cars: Collection of input data for the cost-benefit analysis in this study highlighted the shortage of publically available data for freight vehicles and public transport, despite several European projects trialling C-ITS services in these types of vehicles. **In the majority of cases, the analysis in this project assumed costs and impacts (safety, fuel consumption, emissions, and time related impacts) would be similar for all types of vehicles. Ideally, vehicle specific data collected from a range of FOT projects would be used for improved estimation of the potential costs and benefits of C-ITS services."**

A first step in this direction was made in [122], in which the authors drew a business case analysis that highlighted which stakeholders are the more suited to adopt the technology in the short term, what are the driving factors for their involvement and the perceived barriers through interviews with key fleet executives. In [122], relevant comments and opinions are reported, moreover the following conclusions were derived: First, "(…) over-the-road truckload and less-than-truckload line-haul fleets and private fleets are best positioned as early adopters of DATP [Driver Assistive Truck Platooning], due to their financial resources and operational aspects (…)". Moreover, actual commercial Truck Platooning system should be presented and validated in their capacity to return the investment, clearly proving the needed time horizon and the domain in which the technology is intended to operate.
Generally speaking, an appropriate business case can push an increased number of truck maker to invest on Truck Platooning, greatly increasing obtained benefits in the short term and avoiding the well-known "chicken-egg" situation in which the first ones adopting the innovative system are also the more exposed. This is especially true for a technology like Truck Platooning that expresses its full potential when is shared by a great number of vehicles (and the same can be said about C-ITS services). A greater number of equipped vehicles implies an increased probability of forming a platoon on the road. An in-depth business case can consider, in addition, the opportunity that is the creation of a Platooning Service Provider (PSP) able to coordinate the truck fleet on the European roads and maximize the number of platoons formed.

A relevant work that tries to consider a broader range of benefits bound to Truck Platooning (in order to derive a value case) is [123], based on the discussion paper for Truck Platooning Next Level group meeting (Glasgow, June 2016). Besides the clear benefits due to the reduced fuel consumption, in fact, the authors report two other value cases: maritime container positioning and truck/driver productivity. Both these aspects should be considered while defining the business case for Truck Platooning and the authors, in this work, made first assessments, aimed at providing evaluators and stakeholders with magnitudes, rather than definitive results. As long as container positioning at terminals is considered, the main issue that could be tackled through Truck Platooning is the uncertainties bound to the arrival time of trucks at loading/unloading docks. These variations can range from seconds to hours and make difficult for the managing authority to predict the exact order and, thus, plan how to stack on the container yard (stacks should be aligned for the order of servicing in order to limit the number of repositioning moves with containers). Having a fair share of trucks arriving at the dock together, with a fixed order of trucks, should allow for an easier and more precise planning activity. On the basis of expert evaluations, the authors gave a range of values to relevant parameters to quantify a magnitude of effects bound to this value case:

- future number of containers transshipped at terminals = 35 – 50 million TEU for year
- share of ton*km/year moved by road transport = 40 – 80 %
- number of moves saved on average per container = 2 – 3 moves
- cost of one move = 30 – 40 Euro/TEU

Combining these effects, with a market penetration of the Truck Platooning system equal to 10 – 20 %, the resulting savings could range between 100 and 800 million Euro/year

The other relevant share of benefits considered in [123] concerns the increased daily range that the drivers can cover without breaks. As reported in this work, in Europe the maximum driving time adequately interrupted by a short break is equal to 9 hours (that, in the best case scenario of 80 km/h, correspond to around 720 km), beyond which a longer break is needed. If a greater distance must be travelled, two drivers on-board are needed. Thus, an important assumption was made by the authors: for the driver on the following truck the time counts for 50 % and the two drivers (a platoon of two truck is hypothesized) switch place after three hours. This way the daily travelable distance can reach 960 km/h as reported in [123].

Assuming a range of 1700-3000 billion tonkm/year, a productivity increase by 10 – 30 % and a transport price ranging between 0,1 and 0,15 Euro/tonkm, still for market penetration values equal to 10 – 20 %, the averaged resulting benefits can reach 8,8 billion Euros per year.

Lastly, a relevant consideration is that the impacts bound to the platooning technology are not independent from the technological development of other systems such as automated driving and safety-related innovations. Therefore, it should be evaluated what impacts are completely ascribable to Truck Platooning and what impacts are interdependent, instead.

The most pressing matter to face before the implementation of Truck Platooning is the lack of parameters accepted by everyone, certain and correct. Those parameters are essential to set up economic studies, traffic modelling an evaluation of the impacts on Traffic Efficiency, Environment, Safety and User Acceptance. To give an example, it is still not possible to indicate a univocal value for how many vehicles should form a platoon traveling across Europe or for the headway that must be assumed. Both are inputs needed to determine the reduction of emissions, legislative issues or what could be the best interaction with traditional vehicles. In this report of C-Roads Italy, the bibliographical study will elaborate which are the optimal values in the various scenarios for all the inputs needed to assess the impacts listed above.

2.2 CACC & Truck Platooning

Being equipped with the CACC grants the truck platoon an important capacity: shockwave damping. The communication between vehicles clears, indeed, the driving from all the human errors that produce perturbations and instabilities upstream the traffic flow. This is achieved by designing appropriate algorithms that can assure the longitudinal control of each vehicle, tuning speed in a way that each brake of the leading vehicle is absorbed inside the platoon itself. It is important to note that all these positive effects on the traffic flow are achieved both thanks the reduced headway and the communication V2V that allows the following vehicles to brake almost in the same moment as the leading vehicle, this means that those considerations aren't replicable for the Adaptive Cruise Control that accounts for major headways and no inter-vehicular communications. In literature still doesn't exist a univocal answer concerning the impacts of the ACC function on Traffic Efficiency.
A review focused on the improvement of traffic flow thanks to the CACC system was carried out in [91], not only analysing works about augmented capacity on the road and string stability but also accounting for the potential of V2V and V2I communications.

Ploeg, J., Serrarens, A.F.A. And Heijenk, G.J., 2011. Connect & Drive: design and evaluation of cooperative adaptive cruise control for congestion reduction

Another paper that addresses this topic is [90]. The authors designed a CACC system and evaluated its impacts on congestion, considering even the application on Truck Platooning:

“Although the main CACC objective is to increase road throughput, the first commercial application of CACC is foreseen to be in truck platooning, since short distance following is expected to yield significant fuel savings in this case”

It is worth noticing that in this design, the WIFI communication between vehicles is seen as another “virtual” sensor that, together with the on-board radar, tracks the object vehicles from which the headway is kept (a similar approach is followed by VOLVO [94]). The spacing policy adopted is a constant time-headway one: $d_{r,i}=r+hv_i$ where h is the time headway, v_i is the velocity of the vehicle *i* and *r* is the standstill distance. The authors put in evidence how the choice of vehicle i is fundamental as a design choice, the vehicle sending the information can be indeed both the one leading the platoon and the one ahead.

The one carried out in this paper is the logic of transmission in which the contribution of V2V communications is the possibility to share information regarding the acceleration of the preceding vehicles that cannot be measured by the radar. This way the velocity perturbations are dampened and the headway stands still without dangerous oscillation that could lead to collision. The behaviour of this CACC system is string stable. Another important consideration in this paper concerns the V2I communication with Road Side Units that are meant by the authors to influence the main CACC parameters like speed and headway time (it is explicitly reported the possibility to use those communication “to automatically handle merging maneuvers at up-ramps by creating sufficiently large gaps, initiated by the RSU”). In the conclusions a numerical value of 0,7 s for the time gap is reported as string stable, resulting from tests and simulations of this CACC system.

J. C. Zegers, E. Semsar-Kazerooni, M. Fusco And J. Ploeg, 2017. A multi-layer control approach to truck platooning: Platoon cohesion subject to dynamical limitations [32]

An important thing to consider, while dealing with CACC algorithms, is that not every heavy vehicle has the same braking and acceleration features. Therefore, a truck platoon must drive without asking to the single trucks more than they can perform, this means that the leading vehicles, who is the one defining the vehicles motion state, has to receive the possible limitations from all the following ones. An example is the maximum acceleration achievable by the platoon, if the leading vehicle accelerates more than the following ones can it is obvious that the headway between them is going to increase, leading to cut-ins from external vehicles or even to the disaggregation of the platoon. This subject is examined in [32], where a multi-layer approach of the CACC system is presented.

> “In this paper, heterogeneity in terms of the maximum acceleration capability is considered. For a heterogeneous truck platoon, such limitations in acceleration capability can lead to undesired behaviour. For example, variations in terms of payload heavily affect the vehicle acceleration capabilities. In certain scenarios, e.g. dense traffic or hilly terrain, this can

eventually lead to a platoon breakup or other vehicles cutting in between. Since it is desired for the vehicles in a platoon to stay together, it is required to have an enhancement in control strategy and communication topology design. To this end, this paper presents a multi-layer approach to Cooperative Adaptive Cruise Control (CACC)."

As stated by the authors: "the objective of the design is to guarantee that the vehicles in the platoon keep their desired relative position, while maintaining desirable platoon properties in terms of disturbance attenuation". The proposed system is divided in two layers, the lower one uses a unidirectional communication in the upstream direction to let the leading vehicle send its motion state to the following ones. The upper layer is meant, instead, for the following vehicles to send a coordination variable in the downstream direction, this way the leading vehicle can receive possible limitations in the driving due to acceleration capabilities or the maximum engine torques of the following vehicles. It is worth noticing that also this work adopts the same spacing policy employed in [90].

[32] accounts for critical scenarios like different engine capacities, maximum braking values, communication delays, different loaded weights and, especially, slope effects on the platoon maintenance and on string stability. Values of maximum acceleration different between trucks, can, indeed, cause the platoon dissolution when on up-hill traits. This happens if the leading vehicle drives without knowing that the following ones can't keep up with its acceleration values and the circumstance is worsened by the slope of the road.

The longitudinal vehicle dynamics are defined as follow:

$$\dot{q}_i = v_i$$
$$\dot{v}_i = \frac{1}{m_i + m_{eq}}\left(\frac{\eta_T i_d}{R_w} T_i - C_{rl} v_i^2 - m_i B_{rl} v_i - m_i A_{rl} cos\alpha - m_i g sin\alpha\right)$$
$$\dot{T}_i = -\frac{1}{\tau_i} T_i + \frac{1}{\tau_i} T_{ref,i}(t - \theta_G)$$

Where:

- qi represents the position
- vi is the speed
- Ti is the drive torque
- Tref represents the desired torque
- τ is an actuation time constant
- ΘG is the actuation response delay
- mi represents the truck mass
- Arl takes into account the road surface

- Brl considers the internal friction
- Crl accounts for the drag force
- ηT is the transmission efficiency
- Rw represents the wheel radius
- g is the gravitational constant
- α is the road slope angle

The spacing policy considered by the authors is described by $d_{des,i}(t) = r + hv_i(t)$ with *r* and *h* being a standstill distance and the time gap. Designing this way, the control system, it is possible to achieve two different objectives: vehicle-following and disturbance attenuation in the upstream direction.

The lower layer allows to meet the vehicle-following objective by the means of:

$$\dot{u}_i = -\frac{1}{h}u_i + \frac{1}{h}(u_{i-1}(t-\theta_C) + k_p e_i + k_d \dot{e}_i)$$

$\dot{u}_i$ being the desired acceleration of each vehicle, h the desired time gap. k_p is defined as the proportional feedback gain and k_d as the derivative feedback gain. θ_C is the communication delay and e_i is the spacing error.
Exploiting wireless communications, the desired acceleration of the preceding vehicle is sent, that is why in the equation communication delays θ_C are considered.
The upper layer lets vehicles communicate upward through a coordination variable ξ defined as follows:

$$\xi_i = f(\xi_{i+1}, y_i)$$
$$\xi_n = f(\xi_n)$$

Where $y_i(t)$ is an information vector that each vehicle broadcasts. This way the coordination variable of each vehicle is updated based on information about itself and on the coordination variable of the following one. The coordination variable received from the leading vehicle contains the maximum allowable acceleration that can be performed by every vehicle in the platoon, considering also the spacing error included in the algorithm.

S. Ellwanger and E. Wohlfarth, 2017. Truck platooning application, 2017

Clearly the same type of issues concerns the deceleration capabilities of the truck in a platoon. That subject is investigated in [50]. This paper discusses the authors' considerations following Daimler's participation to the European Truck Platooning Challenge, also many numerical values regarding the deployed system are reported such as:

- emergency brake a_{EMG} = - 6 $\frac{m}{s^2}$
- comfort brake a_C = - 3 $\frac{m}{s^2}$
- cooperative Awareness Messages rate = 0,1 s
- communication delay considered = 0,1 s
- minimum safe following distance = 7,53 m
- headway adopted = 15 m
- speed of the platoon v = 80 $\frac{km}{h}$

Considering these parameters, the authors obtained the minimum rate between the deceleration capacities of two vehicles in the platoon, equal to 0,883, needed to ensure safety. 15 meters seems to be a safe distance even when the following vehicles have the 88,3% of the braking power of the leading vehicle. In this paper it is stated explicitly that there has to be redundancy between V2V communications and the sensors on-board.

> "Our calculations have shown that it is risky to solely rely on V2X communication as a control input for truck platooning, especially when reducing the safety margin between trucks. This is why we chose to do a sensor fusion of V2X, radar and camera data in our implementation."

During the Challenge only two technical issues were detected. There was a GPS outage of 10 seconds in a valley under a bridge (which caused the dissolution of the platoon) and a badly marked construction vehicle parked on the shoulder of the highway caused an emergency brake warning (and, again, the dissolution of the platoon).

Gordon, M., G., Auburn University 2015. Evaluation of Driver Assistive Truck Platooning on Traffic Flow.

Although different algorithms and parameters of the CACC can change how much the truck platoon affects the surrounding traffic flow, expected impacts are an augmented capacity of the infrastructure and a smoother driving. The latter has been explained above, the former one is achieved instead thanks to the strongly reduced headways. To give some numbers: 0,7 seconds at 80 km/h imply 15 meters between trucks (currently human driving involves for 1 – 1,5 seconds, which means a distance of 26 – 33 meters) so a platoon of four trucks can take up 110 meters while four single trucks can occupy 142 – 163 meters. In [27] the impacts of CACC-equipped heavy vehicles on the traffic flow are investigated. The main objectives of this thesis were: the development of a baseline

case to compare the results with, the definition of the CACC parameters that could be used and the evaluation of the impacts.
The carried-out simulations and the traffic data used concerned a section of the interstate highway 85 in the Auburn-Opelika area, in these simulations three input parameters have been considered: headway, CACC penetration in the heavy vehicles market and traffic volume. As outputs measured to quantify the impact of the CACC system, the author chose: average speed and change in travel time. The choice of the site to analyze in the simulations fell on a predominantly rural area, where the traffic flow was close to the infrastructure capacity but was not completely congested. In that way the benefits deriving from the CACC have been quantified more accurately. Also, in the stretch of road considered there are three exit ramps that represent potential points of conflict and allow simulating more relevant conditions. The author simulated four headway values (1.25 s, 1.00 s, 0.75 s and 0.50 s), the CACC market penetration for heavy vehicles took on five different percentages (20, 40, 60, 80 and 100%) and it is worth noticing that, none of the light vehicles has been considered equipped with cruise control or any other technological equipment. The change in travel time in each simulation was obtained on the basis of the delays of each vehicle and aggregated in a single value. The results obtained by the author show that as the traffic volume increases, the benefits of the CACC are greater and the travel time decreases, this however is not relevant in case of free flow or completely congested flow (an important output of the simulation shows that the presence of CACC-equipped vehicles accelerates the return to a regular outflow). The results show also that subsists a relationship between the average speed of the traffic flow and the headway chosen for the platoons, as the headway drops, the grater the market penetration the higher the average speed achieved, regardless of the traffic volumes. The author concluded that, in general, market penetration must be higher than 20% to lead to significant improvements on traffic flow (considering scenarios comparable to the simulated one). Besides, the headway considered in the short term is 1 s because shorter values must account for acceptance factors, ramps and the uncertainties of the mixed traffic. In the conclusions the author recommends validating those results with field tests and to increase the number of simulated case studies. Another research subject that should be analyzed is about the reserved lane for Truck Platooning, this kind of solution has still to be examined in depth, a solid business case and an exhaustive cost – benefits analysis are still missing.

Deng, Q., 2016. Heavy-Duty Vehicle Platooning: Modeling and Analysis, KTH Royal Institute of Technology

An in-depth study for the CACC algorithm was carried out in [19] were the system was defined by:

$$a_{cacc} = a_1 + k_v(v_1 - v_2) + k_r(r - r_{des})$$

In this equation the acceleration of the preceding vehicle a_1 is considered, this value is the one broadcasted by the means of WI-FI connection and can allow headway values as low as 0,5 seconds without compromising string stability. v_1 , v_2 represents the speed of the vehicles, r is the inter-vehicle distance while r_{des} is the target value of such distance. k_v and k_r are control parameters that have to be tuned empirically. An important subject considered in the algorithm is the limited acceleration capacity of trucks, for each one of them maximum values of acceleration and deceleration were contemplated as functions of the ratio between the pulling force and the mass of each vehicle. Each contribution to the pulling force isn't going to be analyzed in this Ex-Ante report, please refer to [19] for the complete dissertation. Generally speaking, the F_i contributions represent the various resistances that a vehicle of mass M has to overcome.

$$a_{max}(v_2) = \frac{F_{engine}^{max} - F_{air-drag}(v_2) - F_{rolling} - F_{gravity}}{M}$$

To determine $F_{air-drag}$, a coefficient c_D = 0,6 was considered. The maximum deceleration value was set equal to -3 m/s^2. Thanks to this CACC system when the leading vehicle tries to assume an acceleration value higher than the maximum ones achievable by the following vehicles, the platoon adopts the lower value among those. According to the author, limitations in the macroscopic modeling works found in literature are the inability to express the spatial headway as an input able to characterize the traffic flow, to quantify the maximum benefits on the surrounding traffic achievable thanks to the implementation of truck platooning seems to be difficult too. To deal with these issues, different maneuvers of truck platooning were simulated in this work, considering their interaction with traditional traffic and assuming different spacing policies as a function of the density of the traffic flow. This way became possible to assess the impacts of the spacing policies on the surrounding traffic, because the spacing policies themselves were considered inputs in the speed-density relationship. Allowing the spacing policy to change from the distance gap to the time one allows to exploit the benefits of both approaches, using the most suitable for the surrounding traffic. The input used in the modeling work were: % of cars, car length, truck length (plus one meter for the safe distance), the time gap between two cars, traditional trucks and leading vehicles. The speed-density relationship used was the one present in the General Motor's car following model (Gazis, R. Herman, and R. Rothery, 1961). Modeling the free flow scenario, it was assumed that every road user could drive at the desired speed, while in the congestion scenario the same travel speed was considered for every vehicle and no overtaking or lane change maneuvers were considered. Referring to a previous study (Deng Q., Burghout W., "The Impact of Heavy-Duty Vehicle Platoon Spacing Policy on Flow" 2015) the speed-density relationship used was the following one:

$$k(1-P)(L_{car}+v\tau)+kP(L_{HDV}+v\tau)=1$$

Where:

- k is the traffic density
- P is the percentage of heavy vehicle among the traffic flow
- L_{car} is the length of the car, also considering 1 meter of standstill safe distance
- L_{HDV} is the length of the heavy vehicle, also considering 1 meter of standstill safe distance
- τ is the average time gap both for passenger cars and for the leading truck of a platoon
- v is the space mean speed (namely, the aggregate highway velocity for different levels of traffic density)

This relationship was then modified by the author to account for Truck Platooning.

$$k(1-P)(L_{car}+v\tau)+kP[L_{HDV}+r_{des}(v)]+n[v\tau-r_{des}(v)]=1$$

Here, 1 ≤ n ≤ kP stands for the number of assembled platoons and r_{des} is the desired inter-vehicle distance. The spacing policy, then, becomes part of the speed-density relationship expressed with the two equations above. When the flow density reaches an intermediate stage, the author kept the trucks speed equal to the desired one while lowered the speed of the surrounding cars, no more able to travel without conditioning each other. Also in this case the speed-density relationship was taken from the prior study by Deng Q. and Burghout W.

$$v=\frac{k}{\frac{k(1-P)}{v_{car}}+\frac{kP}{v_{HDV}^{des}}}=\frac{v_{HDV}^{des}v_{car}}{v_{HDV}^{des}(1-P)+v_{car}P}$$

It is important to note that the input chosen for space and time gaps where, respectively, equal to 3 m and 0,5 s which are the ones that accounts for the greater aerodynamic benefits along the platoon. With the relationship described above, the simulation suggested how a constant spatial headway leads to substantial improvements in the capacity of the infrastructure while a time gap strategy brings higher performances for very congested traffic flows. To get both benefits, therefore, the author formulated a mixed spacing policy in the form of:

$$k_r=\frac{t_d-r_d\tau+r_dt_d}{P*r_dt_d+(1-P)r_d\tau+PL_{HDV}t_d+(1-P)L_{car}t_d}$$

Where t_d is the time gap assumed with the constant time gap spacing policy and r_d is the headway assumed with the constant vehicle spacing policy.
Besides, different spacing policies were considered in the model to allow the platoon to keep different headway values according to the surrounding traffic states and the infrastructural features:

$$r_{des} = \delta_k r_0 + (1 - \delta_k) r_{large}$$

Where δ_k is related to traffic density and can be equal to both 1 or 0. By applying this equation, the spacing policy can vary between r_0 and r_{large} (which are simply two possible headway values) as a function of the surrounding traffic density. For a more complete analysis refer to [19].

2.3 Human Machine Interface and other human-related factors

It is generally agreed among the different stakeholders that, in the short term, each platooning truck will still have a driver engaged in the driving loop. Also, once reached the 2025 milestone, despite the market stabilization, the technology validation and the legal frameworks adjustments, the drivers will still be on board the following vehicles but out of the driving loop, which means that they will be able to work, engage other activities or rest during the travel. Only on the long term completely automated following vehicles will be seen on the road, which means that, until then, a Human Machine Interface (HMI) will be needed on each truck. The issue is not negligible, in fact one of the most common threat attributed to automation is a lower situation awareness observed in the drivers, besides, both over and under-reliance on the system are equally dangerous. Moreover, it must be considered that travelling with reduced headway results in reduced field of vision for the drivers of the following vehicles. It is important that each driver knows what the system can and cannot do, that his driving experience isn't perceived worsened by the system and that the Truck Platooning itself isn't perceived as a threat for the drivers' job and doesn't raise uprising among them. All these subjects, with the possible exception of the last one, are faced by designing an appropriate Human Machine Interface. An HMI, in fact, is built to allow the automated system to communicate with the drivers which can choose to perform some maneuver through the HMI itself. The most common information attributed to the interface are:

- system engaged/disengaged
- information sent by Road Side Units
- information sent by Traffic Control Centres
- information sent by Platooning Service Providers
- messages between trucks
- maneuvers that the platoon is going to engage

Friedrichs T., Borojeni S.S., Heuten W., Lüdtke A., Boll S., PlatoonPal: User-Centered Development and Evaluation of an Assistance System for Heavy-Duty Truck Platooning, 2016.

In [107], a platooning assistance system named PlatoonPal is presented, developed in order to build trust in automation and reduce the fear of the drivers while driving with close distances. The level of automation considered seems to be L1, only the longitudinal control is automated while the lateral movement of the truck is still entrusted to the driver. PlatoonPal supports four platooning stages: merging, driving in the platoon, external vehicle intruding and splitting.

The drivers must be able to interpret the dynamic context and the correct timing of platooning maneuvers, accounting for the other trucks and the increased space that the platoon as a whole takes up on the infrastructure, this task can be challenging for drivers that have to examine an increased amount of information and to decide accordingly. It is important, then, that the information displayed on the HMI are the most important ones (too many information can even result in a decreased situational awareness), presented in a clear way and with the right timing.

PlatoonPal is designed on the basis of interviews and observations carried out with truck drivers, iteratively selecting and validating the relevant information and the more suitable way to show them on the interface. The first set of interview carried out showed what level of acquaintance the drivers had with the automation, "the main problems that (…) participants could foresee in platooning are lack of trust in the behavior of the driver in the front vehicle, reliance on technology, and lack of knowledge about the driving environment due to the limited field of view." Then first paper prototypes were created, about which the drivers gave some feedbacks such as: Information about the front vehicle is needed and the driving maneuvers of each phase should be presented. Before reaching the platoon, relevant information are the remaining distance, if the merging area can be reached in time (also, the speed required should be showed) and road incidents. Information related to the own vehicle are perceived as the most important, even though for the leading vehicle information about the whole platoon is decisive in carrying out many maneuvers.

The PlatoonPal interface was rated by drivers after test in real word scenarios on a test track, by the means of questionnaires regarding each performed maneuver. It is important to note that PlatoonPal was displayed on a monitor mounted in the instrument cluster of the trucks behind the steering wheel. The tests results showed an increased situation awareness and faster reactions among the drivers. An issue arisen during the tests concerned the merging maneuver during which the drivers had the feeling of losing control, also, with more than one truck at the merging point it wasn't easy to distinguish which was the target one. Besides, acoustic notifications were judged to be useful when provided at the end of the merging and of the splitting maneuvers.

Larburu, M., Sanchez, J. And Josã© Rodriguez, D., 2010. SAFE ROAD TRAINS FOR ENVIRONMENT: Human factors' aspects in dual mode transport systems

[39] is a study, carried out within the European project SARTRE, in which human factors' aspects in semi-automated driving are analyzed. Besides acceptance and comfort, the other issues identified are: the level of situational awareness, the possible loss of skill among the drivers, the workload level, the transitions from normal driving to autonomous/automated driving and vice versa. Also, the readiness of the driver responding to a system failure and his behavioral adaptation towards automation were considered. Behavioral adaptation is the result of the decreased workload and involves reduced safety. It is important, in general, that the system is perceived as more comfortable and safer than driving without it, especially for experienced truck drivers that could trust themselves more than the automation. Also, the drivers should be always aware of the mode the system is in and remain aware of the surrounding traffic, both those challenges can be tackled by a well-designed HMI and haptic or auditory information. Another subject analyzed in [39] concerns the transition phase during the control shift from automation to manual driving and vice versa, a topic on which an extensive literature can be found [21, 45, 54] but dedicated case studies about truck drivers (possibly engaged in other working activities) and truck maneuvers are still lacking. If some scenarios may be less safety-critical because the transition is planned by the driver himself (e.g. leaving the platoon maneuver), system failures can require reaction times unachievable by a distracted driver, especially considering the reduced headways. Again, an HMI able to clearly highlight the problem and the driving scenario can reduce the transition time and make the driver able to take back control with an improved situational awareness (which is often the most time-requiring task in those situations). In the same way, auditory and haptic signals can help the driver re-engage the driving-loop earlier.

Thus, during the study a fixed-base driving simulator was employed to assess both the prominent opinions among other road users while driving near different sized platoons and following vehicle drivers' opinion during the travel in platoon formation. It is worth noticing how the SARTRE project considered platoon composed both from cars and trucks, so the results should be read keeping that kind of scenario in mind, for example driving near a car-composed platoon should be expected to have a different impact on other road user than driving near a truck composed platoon.

For Truck Platooning another acceptance-related subject must be considered, in fact the system should be accepted from the drivers but also from other road users that will have to interact with a platoon. A peculiarity of the system itself concerns the intimidating appearance of multiple queued trucks, recognizable as soon as is reached, and the hindering impacts on the maneuvers of the surrounding traffic. These issues are peculiar of Truck Platooning (except for, possibly, the frightening perception that a car without driver can cause) and should be evaluated before and during the first stages of its implementation.

The study analyzed the intra-platoon gaps too, how the drivers felt for lower values is a result that should be read considering that the drivers where not experienced ones and drove a car, not a truck. Nevertheless, it is worth noticing that for distances lower than 16,9 m drivers felt uncomfortable and for distances lower than 7,5 m drivers felt unsafe, in average terms. Training courses for truck drivers and an acquaintance with the system can both tackle these issues, other parameters considered were gender and ages. Also subjective results were considered, about 73% of test participants stated that a gap of 10 m was adequate for them, this percentage dropped to 54,55% for a gap of 7,5 m.

2.4 Fuel consumption – headways and platoon formation

One of the most important benefits resulting from driving in a platoon is the reduced air drag. This is due to the shorter headway that won't allow the creation of vortex between the vehicles, this means that the drag that the engine must overcome is lesser and so is fuel consumption. The benefits of this feature are particularly relevant, lesser fuel consumption means lower emissions and an economic stimulus for truck manufacturers to employ the technology.

In [11] some studies are cited, in which the consumption due to the air resistance can reach up to 50%, obviously this value only serves as an example for the potentialities since the result itself depends on the atmospheric conditions, air density values, traffic conditions, speeds, headways, etc. Besides, in the same paper, the authors report that road transport is responsible for at least 72% of emissions in Europe, a quarter of which is attributable to freight transport. In [1] freight transport is held responsible for 30% of on-road CO_2 emissions while representing only 4% of the total on-road fleet in the EU. Therefore, reducing fuel consumption for heavy vehicles is certainly a priority and Truck Platooning can help to achieve this environmental benefit. Furthermore, considering what is stated in [36], i.e. that the fuel cost represents about a third of the operational cost for a heavy vehicle, the economic benefits for the companies adopting the Truck Platooning system are clear. These benefits must be assessed with precision, which is extremely important because only a solid business case can persuade companies to invest and cooperate. This assessment is, again, made difficult by the variability of the parameters needed to quantify fuel consumption, moreover, the coordination strategy of the fleet and the road network analyzed have a huge effect on the result. A mono-brand platoon, for example, that starts already in formation and doesn't vary its composition until its destination, it's probably the easiest operational solution but, also, the less profitable. A scenario in which every truck on the road can join or leave a platoon, under the coordination of a Platooning Service Provider, really increases the number of kilometers driven in formation and greatly lowers fuel emissions. Even knowing the exact fuel consumption rate of each vehicle who travel in formation is not enough to assess completely economic and environmental impacts, it shouldn't be neglected how the surrounding traffic can influence the number of kilometers travelled in a platoon formation. Partially congested traffic flow can delay or completely hinder the platoon formation, moreover vehicles eager to overtake, cut-ins, ramps, weather conditions and other external factors can all impose platoon disaggregation and an increased number of acceleration and deceleration maneuvers. So, in this paragraph, only works regarding the relationship between air drag or coordination scheme and fuel consumption will be analyzed, leaving to the following paragraphs the bibliographical overview regarding the interactions between the platoon and the traffic flow.

Lammert, M.P., Duran , A., Diez , J., Burton , K. And Nicholson , A., 2014. Effect of Platooning on Fuel Consumption of Class 8 Vehicles Over a Range of Speeds, Following Distances, and Mass

In the research project reported in [87], the fuel consumption in two Class 8 tractor-trailer combinations platooned together was assessed, this result was compared with the standalone fuel consumption. Ten track tests were carried out changing the values of speed, headway and gross vehicle weights, the trucks were equipped with DSRC, braking control interface, torque control interface, cameras and Human Machine Interface. Designing the test, the possible variations in speed imposed on the platoon by the surrounding traffic were considered by imposing a variable speed profile, on a distance slightly shorter than the circuit in order to take into account possible driver errors while adapting to the set speed values. The disaggregation of the platoon after a gear shift or braking by means of the brake pedal was also imposed. The drivers could slow down to stay compliant with the established speed profile only by engine braking. The tests method recommended in SAE J1321 Fuel Consumption Test Procedure – Type II (1986) was adapted in two points to be applied to Truck Platooning. The first change was about the comparison of results between platoons and the vehicle that provided the baseline data. This vehicle drove behind the platoon 3 or 5 minutes later and its results were compared independently with each one of the trucks platooned. The second adaptation concerned the use of a solenoid valve that allowed to move from a tank dedicated to the warm-up phase to the quoted one reserved for the route and from which the results were acquired. The tests were carried out according to the following steps:

- end of the warm-up phase, every vehicle has the same speed and holds the desired headway;
- when every vehicle passed a predetermined point, fuel consumption shifts from the first tank to the quoted one. Desired data start to be collected;
- after finishing the seventh round of the track, every driver reactivates the solenoid valve.

Once the test was completed the results were recorded and compared on the basis of the T/C ratio which is the ratio between the fuel consumed by the vehicle platooning and the baseline one. Also, the rate given by the sum of the fuel consumed by the two vehicles platooning was compared with the baseline value. Measurements varying more than 2,5% between the various tests were not considered, the only exception being the speed measurements in which greater oscillations were probably caused by slight driver mistakes, made adapting their driving to the communicated speed profile. During the tests measurements about the environmental characteristics were recorded too:

- temperature
- relative humidity
- barometric pressure
- average wind speed
- peak wind speed
- wind direction

All these values affect fuel consumption and savings deriving from Truck Platooning, for each one it is fundamental to identify these relationships. For the whole set of outputs please refer to [87].
The spatial headways used during the tests can be converted in time gaps ranging between 0,2 and 0,8 seconds. A result worth noticing is how the temperature of the coolant increases as the headway decreases, this involves a greater use of the fan on the front of the following vehicle and causes lower aerodynamic savings. The coolant temperature seems to be a relevant parameter to consider to choose an optimal headway value. A similar effect is mentioned in [35, 112] as an event characterized by low incidence and probability. By the numerical outputs obtained in [87] can be derived how, in general, higher wind speeds increase the fuel savings for the leading vehicle while lower temperatures reduce that value. The maximum reductions in fuel consumption achieved were 5,3% for the leading vehicle and 9,7% for the following vehicle but the authors have highlighted how these values were not obtained during the same test. Besides, these percentages are mostly in line with the ones commonly found in literature (≈ 4% for the leading vehicle, ≈ 10% for the second one and ≈ 14% for the last one in a platoon of three [104]), it must be noted how those values can change due to the number of the vehicles forming the platoon.

D. Bevly, C. Murray, A. Lim, R. Turochy, R. Sesek, S. Smith, L. Humphreys, G. Apperson, J. Woodruff, S. Gao, R. Bishop, D. Murray, A. Korn, J. Switkes, S. Boyd, B. Kahn, "Heavy Truck Cooperative Adaptive Cruise Control: Evaluation,Testing, and Stakeholder Engagement for Near Term Deployment: Phase Two Final Report", FHWA Task Report, April 2017.

The tests carried out in [87] were deepened in [122] in which the results of a similar test framework were reported. The project was led by Auburn University together with a project team from Peloton Technology and was developed for two main reasons: the Peloton technology in the recent years was enhanced further and became able to address some issues concerning fuel consumption (namely the rate of change in demanded torque increase with lower time gaps and the engine fan activation during previous field tests), moreover, these field tests provided the Auburn University with real world data useful for the Platoon CFD (computational fluid dynamics) modelization. As mentioned above, the field test design results rather similar to the one applied in [87] (both are based on the SAE J1321 – Type II procedure and apply similar adjustment in order to consider the peculiarities of Truck Platooning). To avoid unnecessary redundancy in the dissertation, only the results and relevant aspects of [122] are going to be reported in this paragraph, please refer to [122] for the complete dissertation and the complete list of results and field test indicators recorded.

The environmental conditions were recorded through an electronic weather station that measure the temperature, relative humidity, average and peak wind speed, wind direction and the barometric pressure.

From the test resulted that the highest fuel savings obtained for the following truck in a two trucks platoon is equal to 10,24% for a headway of around 15 m while the highest value for the leading vehicle is equal to 5,27% for a headway of around 9 m. The most interesting feature arising from the field tests is that the fuel savings are not monotonic with the distance for the following vehicle which apparently contradicts with most of the results of modeling works such as the computational fluid dynamics modelization carried out within the Auburn University itself. The authors, then, researched the most likely cause that could be accounted for such a phenomenon and concluded that the possible cause lies within the effects of lateral offsets between the leading vehicle’s trajectory and the following vehicle’s one.

From the results it seems that the leading vehicle doesn’t suffer from the lateral error between itself and the following vehicle while the following vehicle sees the aerodynamic effects worsening. The authors hypothesize that this effect is caused by the exposed surface of the following truck that faces the undisturbed free-stream flow. Thus, an asymmetrical pressure is generated and must be overcame, this effect seems to be enhanced for reduced headways as the wake of the leading vehicle doesn’t dissipate in the longitudinal direction. From the test carried out resulted that the magnitude, the frequency and the duration of the lateral offset negatively impacts on the aerodynamic performance of the following vehicle. The time during which the lateral offset resulted greater than around 0,3 m decreased as the headway decreased, suggesting that the following driver, still in charge of the lateral control, finds easier to minimize the offset while being close to the leading vehicle. Another relevant factor that could worsen the aerodynamic performance of the following vehicle is the lateral oscillation of the following truck, trying to stay correctly platooned (this factor could prove to be difficult to measure, especially through GPS data). Again, the oscillations resulted reduced for lower headway values. It should be noted that, in platoons composed by two heavy vehicles, the aerodynamic benefits enjoyed by the leading vehicle seem to overcome the shortcomings bound to lateral oscillations (which grow when the headway lowers), thus making the lowest feasible headway the optimal value nonetheless (as long as fuel consumption is concerned). Moreover, the leading vehicle doesn't seem to suffer from a not-aerodynamic surface of the following vehicle which means that the vehicle with the most aerodynamic surface should be the leading one in order to minimize the overall fuel consumption.

Besides, it should be highlighted that the controller dither (bound to the variation in throttle control needed to maintain the separation distance) didn't impact the trend of fuel savings in the following truck and the same resulted valid for the engine coolant temperature that contributed only for a small part in the trend of fuel consumption related to the headway value. Avoiding the activation of the engine fan in the carried-out tests allowed to avoid the decrease of the fuel savings for the following truck at lower headway values.

Within future research directions, the authors considered the differences in aerodynamic profiles of trucks and trailers and what impact this could have. It is stated that this assessment is still to be studied in field tests. Moreover, the impact of factors such as model, engine, transmission, brake system and aerodynamic packaging should be analyzed in their effect on the non-monotonic fuel consumption trend (that could be also related to lateral offsets but, according to the authors, additional research effort is needed on this subject).

Deng, Q., 2016. Heavy-Duty Vehicle Platooning: Modeling and Analysis

[19] is a work that addresses many subjects regarding Truck Platooning and is going to be cited in other paragraphs too. Here, the fuel consumption model[1] assumed by the author and the parameters employed are relevant.

$$f = \frac{\int_{t_0}^{t_f} \delta[\mu cos\vartheta + sin\vartheta)M_{gv} + kv^3 + M_{av}]dt}{H \cdot \eta}$$

H and η represent energy density and efficiency, v is the vehicle's speed, α the acceleration, M the mass and δ is a variable that states if the engine is on or off. The *k* coefficient stands for aerodynamic drag and is derived from $k = \frac{1}{2}\rho_a A_a c_D(1-\varphi)$, where ρ_a is the air density, A_a the vehicle front area and c_D the air drag coefficient. In this model φ is null for the leading vehicle while, for the following ones, the values reported by Wolf-Heinrich and Ahmed in Aerodynamics of Road Vehicles (1998) are adopted.

The only parameter ignored in this model is the slope of the road. Once defined the model, an air drag reduction of 6% was employed and the author analyzed the impact of Truck Platooning on the overall traffic flow. An interesting result is that, increasing the percentage of truck platoons, the energy efficiency of the other vehicles seems to increase too. The author guesses that this could be

[1] This model was proposed by Oguchi et al. (2002)

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the result of a lower number of lane changing maneuver and consequent accelerations and decelerations (due to the capacity to overtake more than one heavy vehicle with a single maneuver).

In literature many values for the reduction in fuel consumption are listed, it seems appropriate to list few to give an order of magnitude for the phenomenon. In [35], for example, it’s clearly stated how, in a platoon composed of two trucks, the following one obtains a fuel reduction of 8-13% while the leading one achieves values of 2-8%. As an approximation, in this work, a value of 0,25 liter per kilometer is considered and the reductions are equal to 2÷3,3 L per 100 km for the following vehicle.

> “Since we look at two-truck platooning, we can use the average of the Leading and Following Vehicle in our calculations. We work with an average fuel saving of 10% per truck driving in a platoon. With a diesel price of € 1.20 per liter and a usage of 0.25 liter per kilometer, two trucks driving 100,000 kilometers annually, platooning can save € 6,000 on fuel compared to driving with cruise control.”

In bibliography, a great number of studies focusing on the benefits of a Platooning Service Provider can be found, many of which assume a mean reduction in fuel consumption for the whole platoon. In [36] a 10% reduction is applied to the following vehicle while the reduction for the leading one is neglected, the same value is assumed in [33] and in [41] also for the leading vehicle. In fact, the first truck benefits from the platooning formation as the pressure between itself and the second truck is higher and the engine can expend less energy overcoming this pressure zone (the needed energy is higher for lower pressure values) [105]. Similar considerations were made in [122] in which the benefits of the leading truck are considered as consequences of breaking the recirculation zone behind it thanks to the following vehicle travelling really close. In this work, platoons composed by three trucks are evaluated too in their aerodynamic performance and resulted that the truck in-between outperforms the rear truck only when the headways are so low that it receives benefits both as following truck of the leading one and as preceding truck of the rear one (i.e. if the recirculation zone is broken). If that is not the case, both the truck in-between and the rear one enjoy similar air drag reductions.

In [51] the air drag for the following vehicles is assumed reduced to 60% and the fuel consumption model is $f(v) = F_r + F_a v^2$, where F_r accounts for the rolling resistance and F_a for aerodynamic forces. As stated by the authors, this is a simplified approach that does not account for selected gear, road grad, wind and other influencing factors (these are recurring assumptions in these works). The same air drag reduction is found in [62], where, again, a 10% fuel saving is considered and in

[11] where the fuel saving is considered equal to 9-15%. In [1] some results of SARTRE “D.4.3 Report on Fuel Consumption”[2] are listed and commented:

The reductions in fuel consumption can “(…) range from 2% to 8% for the leading vehicle and from 8-13% for the following vehicles according to the SARTRE project. The fuel savings of a platoon as a whole can thus range from about 5% to 10%. As fuel costs weight on a truck’s operational costs by 30% on average, the prospect of reducing it, along with the fierce competition in the transport sector that operates on small profit margins, is an important factor in the adoption of truck platooning. These fuel savings correspond to a reduction in CO_2 emissions by 5% to 10%.”

Similar ranges are considered in [15], where a range of 5-15% is considered, or in [99] where fuel savings range from 2 up to 12% with a spatial gap of 20 m.

While defining a business model for Truck Platooning, the COMPANION project accounted for lower values in fuel savings, considering 5% for each vehicle [6]. Other values lower than average are the ones considered in [69], still equal to 5% and in [37], equal to 6,5% (driving at highway speed with 1 s time gap).

McAuliffe, Brian R.; Croken, Mark; Ahmadi-Baloutaki, Mojtaba; Raeesi, Arash - Fuel-economy testing of a three-vehicle truck platooning system

[116] is a report based on a test program aimed at assessing the influence of headway, speed, truck configuration (aerodynamic vs traditional shape) and weight on fuel consumption for a three-truck platoon. The tested headway ranged from 17 to 43 m (0,6 s ÷ 1,5 s) and the driving speed ranged from 89 to 105 km/h.

An important result obtained by the authors is the comparison between traditional shaped trucks and aerodynamically shaped one, from their bibliographical review, in fact, it appears that different geometrical features at the frontal surfaces of the trucks impact on the aerodynamic drag and, thus, on fuel consumption. This can seem obvious from the start but this change in aerodynamic drag seems to affect also the air pressure between platooned trucks and thus the aerodynamic features bound to the platoon formation. On the basis of the works[3] analyzed by the authors it appears that the preceding vehicle shields the following ones and “reduces the suction or thrust force on the curved frontal surfaces of the following vehicle” too. When the distance between platooned vehicles

[2] Applus + IDIADA 2014

[3] Smith, J., Mihelic, R., Gifford, B. and Ellis, M. (2014), “Aerodynamic Impact of Tractor-Trailer in Drafting Configuration,” SAE Int. J. Commer. Veh., 7(2), doi: 10.4271/2014-01-2436.

Gheyssens, T. and Van Raemdonck, G. (2016), “Effect of the Frontal Edge Radius in a Platoon of Bluff Bodies,” SAE Int. J. Commer. Veh., 9(2), doi: 10.4271/2016-01-8149.

is small enough, the reduction of the suction becomes dominant compared to the shielding effect of the preceding vehicle which results in lower aerodynamic benefits. Like [87], this test experiment was designed on the basis of the SAE J1321 Type II procedure and was performed at the Motor Vehicle Test Centre operated by PMG Technologies in Blainville, Quebec.
Three kinds of runs were carried out during the experiment:

- baseline test segment, through which the baseline scenario was assessed;
- independent vehicle test segment, during which changes were made to the test vehicles;
- platooning test segment, during which the platoon was spaced approximately 3,2 km from the control vehicle.

On the basis of SAE J1321 and, therefore, similarly to what has been reported in [87], the fuel consumption results have been analyzed on the basis of the T/C ratio equal to:

$$\frac{T}{C} = \frac{\Delta W_{F,test}}{\Delta W_{F,control}}$$

Where ΔW is the weight of the fuel consumed both for the test vehicles and the control vehicle during the run. To assess the impact on fuel consumption of the aerodynamic devices equipped on the vehicles, the following equation was considered:

$$\Delta F_{PA/S} = \frac{\Delta F_{\frac{PA}{A}} - \Delta F_{\frac{S}{A}}}{1 - \Delta F_{\frac{S}{A}}}$$

Where $\Delta F_{PA/S}$ stands for the fuel savings achieved by the platoon with the aerodynamic devices compared to the case with the traditional trailer (and, thus, without the aerodynamic devices). $\Delta F_{PA/A}$ represents the fuel savings comparison between the platooned vehicle with the aerodynamic trailer and the aerodynamic trailer driving alone. In the same fashion, $\Delta F_{S/A}$ represents the fuel savings comparison between the traditional trailer and the aerodynamic one. For a complete analysis of the uncertainties related to this kind of approach please refer to [116], it should be noted, though, that the wind-averaged-drag coefficient considered is equal to 0,57. The measured fuel consumptions varied between runs with a variability equal to 7%, the authors ascribed this variability to the changes in the environmental conditions such as wind speed, temperature and relative humidity. Thus, on the basis of the obtained results, the authors made considerations about the headway and speed values. The vehicle in the platoon that experienced the highest fuel savings was the last one, a result different from the most common ones found in literature (in which are the vehicles in the middle of the platoon that consume less). The authors hypothesized that for headway values lower than the ones tested, the trend could change and the middle vehicle could enjoy the highest reduction in fuel savings (statement made on the basis of their literature review). Moreover, fuel consumption in the leading vehicle didn't change thanks to the platoon formation, for the headway values tested at least, the authors commented the results with the following considerations:

> "The negligible change in fuel savings for the lead vehicle provides some evidence to explain the differences between the middle and trailing vehicles. If the lead vehicle does not experience a measurable fuel savings at the shortest separation distance, it would therefore not be expected that the middle vehicle experiences any influence of the trailing vehicle. The middle vehicle fuel savings is therefore dominated by the low-speed air-wake of the lead vehicle. The trailing vehicle experiences a greater fuel savings than the middle vehicle likely due to a compounding effect of the low-speed air-wakes of the lead and middle vehicles, producing an air-wake with a greater wind-speed deficit (relative to the moving vehicles) than the air-wake of an individual vehicle".

Comparing the traditionally shaped trucks with the ones aerodynamically equipped, some interesting results from the report can be reported: for example, for a headway equal to 17,4 m the traditional trucks recorded fuel savings equal to 7,4% and 11% respectively for the second and third position along the platoon, while when aerodynamically equipped, these value became 9,4% and 12,3%. In the same fashion, for the highest headway value tested, the same percentages arose from 6,2% and 9,5% to 6,7% and 10,4%. As long as the speed ranges between 89 km/h and 105 km/h, no significant impact on fuel savings arises from a change of driving speed of the platoon.
Finally, some general results obtained by the authors (considering all the test conditions that were modified during the tests) should be reported:

- the fuel savings for the whole platoon can range from 5,2% to 7,8%;
- combining the platooning effect with aerodynamic devices can produce fuel savings up to 14,2% with a headway of 17,4 m;
- the aerodynamically equipped trucks experienced fuel savings greater than the traditionally shaped ones (0,5% ÷ 2% depending on the considered headway value);
- a detailed analysis of the CAN bus data should be performed to provide additional characterization of the aerodynamic and control-system performance of the vehicle platoon (also considering the straight and banked sections of the track).

Andersson, Jonas, Englund, Cristofer, Voronov, Alexey, 2017. Study of communication needs in interaction between trucks and surrounding traffic in platooning

In [7] another important value is reported, instead. The study focuses on the losses in fuel saving due to another vehicle's cut-ins in the platoon and the resulting disaggregation. The number of these maneuver is strongly related to the headway value that affects not just the air drag reduction but also the number of vehicles that fit themselves between two trucks. The authors considered 3 cut-ins/100 km that cause a loss of 0,1 litre/100 km in fuel savings. This value should be considered just as an example; the number of cut-ins is strongly related to external factors like the surrounding traffic flow, the kept headway and also cultural influences (influencing the driving behaviour and the aggressiveness of the overtaking maneuver). For example, the authors report how data from naturalistic studies in the USA indicate the absence of cut-ins for headways lower than 30 meters. In Europe, during the European Truck Platooning Challenge (where a headway of 1 second, corresponding to 22 m, was chosen), the results showed a cut-in every 15 km, instead. The differences in behaviour, however, can be found even when looking at a more circumscribed level, in Sweden the cut-in phenomenon is very rare while, on networks such as the German or the Dutch ones, it is a more widespread phenomenon, also due to a higher traffic density. The model employed to assess the loss of savings in fuel consumption during a cut-in is the one developed by Voronov A., Andersson J. and Englund C. The fuel consumption is considered proportional to the energy acquired from the fuel itself, so $m_{fuel} = \frac{E_{fuel}}{c_p^{diesel}}$, where E_{fuel} is the total energy contained in the fuel and c_p^{diesel} is the diesel's specific energy density. Considering a dissipation of 65% of this energy, the remaining part should be enough to overcome gravity in the road sloping traits, rolling resistance and air drags. This means that $m\dot{v} = F_{wheel} - F_{air} - F_{roll} - F_g$ where m is the vehicle's equivalent mass, v the longitudinal speed, $F_{air} = \frac{1}{2}\rho_a c_d A_f v^2$ and F_g the gravitational drag. If it is considered $F_{fuel} = \frac{dE_{fuel}}{dx} = \frac{F_{eng}}{\eta}$, where η is the engine efficiency, m_{fuel} can be derived from the equation of vehicle dynamics.

$$\frac{dE}{dx} = F_{eng} - F_{brk} - b_{air} * E - F_{roll} - F_g$$

Where F_{brk} is the braking force and $b_{air} = \frac{\rho_a C_d A_f}{m}$. Then:

$$m_{fuel} = \frac{1}{c_p^{diesel}} \int_{x_1}^{x_2} \frac{1}{\eta(x)} F_{eng}(x) dx = \frac{1}{c_p^{diesel}} \int_{t_1}^{t_2} \frac{1}{\eta} \left(\frac{dE}{dx} + F_{brk} + F_{air} + F_{roll} + F_g \right) v dt$$

With this model the authors assessed fuel consumption, assuming the following statements:

- a cut-in nullifies all the aerodynamical benefits in a platoon
- a 10 m headway implies a 40% reduction in aerodynamical drag
- aerodynamical drag affects for 1/3 the total fuel consumption (considering a 40t truck), this means a 13% reduction in fuel consumption while in platoon formation.
- for an ordinary topographical route (from the Swedish point of view), fuel consumption is 30 litre/100 km for a single truck driving alone.
-

Assuming all of the above, the fuel savings resulting from Truck Platooning are equal to 4litre/100km (10 – 15%). For a 45 seconds cut-in the loss in fuel savings is determined by:

$$m_{lost} = \gamma_{platoon} * \gamma_{air} * m_{fuel} * \frac{n_{cut} * d_{cut}}{100km}$$

Where n_{cut} is the cut-ins number on a 100 km section and d_{cut} is the mean distance driven by the intruding vehicle while inside the platoon. $\gamma_{platoon}$ is the air drag reduction for the following vehicle and γ_{air} is the proportion of fuel necessary to overcome the air resistance.

Overview

It is not possible to determine a single value or a relationship that allows the assessment of reductions in fuel emissions on the basis of the works analyzed above. This is because that value doesn't depend on only the characteristics of the platoon (like headway, speed, number of vehicles, position across the platoon, etc.) but also on the environmental features (like temperature, air density, wind speed, etc.), social behaviour, surrounding traffic, road grade etc.

Figure 1 - IVECO trucks - Aerodynamic benefits

Later in this report will be defined, based on what has been examined in Chapter 2, how to evaluate fuel consumption and environmental benefits bound to Truck Platooning and to its jointed implementation with C-ITS. Below are summarized all the essential subjects that should be considered while defining fuel consumption, according to literature.

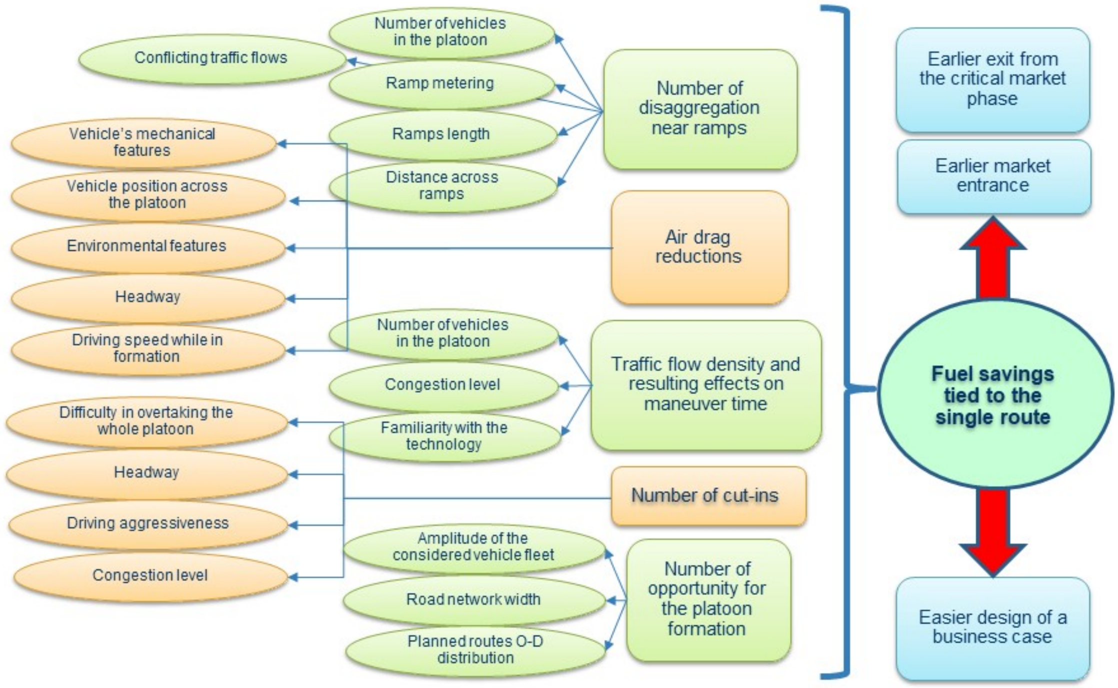

Figure 2 - Single route fuel consumption

2.4.1 Platoon Coordination Strategies

The above information allows to evaluate the fuel savings linked to a single travel and to the kilometers that the truck travels in formation. Many of the works in the literature, however, went further and analyzed how a Platoon Service Provider, as coordinating body, could greatly increase the number of platoons assembled on a road network compared to the mono-brand case. The spontaneous truck platooning formation on the road is a phenomenon that accounts for 1.2% of the fleet, which correspond to a fuel savings increase of 0.07% compared to the case of total absence of platooning on the road network [36]. In fact, many of the drivers are aware of the benefits related to fuel consumption achievable while keeping a lower distance from the preceding heavy vehicle. However, if we assume a service dedicated to the coordination of the vehicle fleet on the road, the arrangement in platoons and the identification of the optimal merging points, the percentage of vehicles involved in platoon formations significantly increases. This type of solution implies the existence of an optimization model that can be applied to the road network and considers the origin-destination matrix of the trucks involved, their arrival times, traffic densities and the redistribution of benefits among the participating transport companies.

Van De Hoeff, S. 2016. *Fuel-Efficient Centralized Coordination of Truck Platooning, KTH Royal Institute of Technology.*

In [62], for example, the coordination problem concerning a fleet composed by heavy vehicles is faced. Each truck participating in this multi-brand solution is characterized by an origin, a destination, the departure time and the arrival time. All these parameters are known by the super-partes service provider, the vehicle, in fact, sends this information through the infrastructure (by the means of V2I communications) to the "platoon coordinator" that computes a plan as efficient as possible in decreasing the total emissions on the road network and then broadcasts the suggested driving strategy (called "vehicle plan") to the vehicle.

The vehicle paths are compared and, if overlapping even only for a limited segment of the route, the opportunity to form a platoon is evaluated. This process is computationally very demanding so, in this thesis, an approach based on "features" is proposed, these "features" are bound to each vehicle's route and are compared to determine which pairs of vehicles can form a platoon, a priori, limiting the number of iterations needed. The optimization problem's outputs are both a route and a sequence of speed values which shift when the vehicle reaches specific points, a vehicle plan is valid if the vehicle still arrives at its destination on time without overspeeding.

An assumption of the thesis is that the leading vehicle doesn't benefit from the platoon formation and consumes the same fuel quantity as if travelling alone, which is a semplification (for example, in [15] the experimental results show instead that the air drag for the first vehicle decreases constantly as long as the headway decreases up to a certain value, beyond which the air drag remains constant). Fuel consumption for the following vehicles has been implemented in the optimization model as follows.

$$F(\varphi_n, \pi_n) = \int_{t_n^S}^{t_n^A} f\big(\varphi_n(t), \pi_n(t)\big)\varphi_n(t)dt$$

Where φ is the speed on the road segment, π the platoon trajectory, t^S the departure time and t^A is the arrival time. f is a generic function that bounds fuel consumption to speed, in this work two functions were considered:

$$f_0(v) = 8{,}4159 * 10^{-6}v + 4{,}8021 * 10^{-5}$$
$$f_0(v) = 8{,}4159 * 10^{-6}v + 4{,}8021 * 10^{-5}$$

The first one concerns the leading vehicle while the second one concerns the following ones. The author chose to ignore the mechanical characteristics of each vehicle and the road grade influence to not make the dissertation too long and complex. However, the lack of parameters about different truck models is still an obstacle to the definition of a reliable business case. It is essential to verify that the vehicles in a single platoon have similar acceleration and deceleration capacities to avoid that lower acceleration achievable by the following vehicles lead to an increase of the headway and to an accidental disaggregation of the platoon (this subject will be discussed further in the following paragraphs).

Then, in the optimization model, the total fuel consumption on the road network was defined by the means of a simple sum on all the composed platoons. As mentioned above, since the computational complexity in calculating each possible platoon is high, “features” are defined through which to determine a first set of vehicles able to join in different platoon combinations. This set of possible platoons is wider than the real one, in the sense that some false-positives are spared to be eliminated in a following stage when the algorithm actually compares routes and timing from this already partially screened set of platoons. For the first “feature” definition, the possible trajectories are projected on a line which yields an interval, if the projection does not overlap the routes have no edges in common. Another feature concerns the orientations of road segments across the planned route and is a binary characteristic. If two itineraries partially overlap, there must be at least one edge with the same orientation, moreover segments with the same orientations but shorter than a certain value can be discarded while searching for potential routes on which truck platoons can be composed (it should be highlighted how a truck, to reach the leading vehicle, must accelerate and consequently consume more fuel, the length of the route travelled in formation should be at least sufficient to recover this increased fuel consumption). This approach based on features is designed to include each possible platoon formation, the author judged preferable having false negatives that could be removed by the means of a control algorithm rather than lose some platooning possibilities. Once the solution of the optimization problem has been defined by the platoon coordinator and transmitted to the vehicles, these should adopt the optimal speed values in order to reach the meeting point, with the lowest fuel consumption, in the established time. It is important to note that, for the algorithm to work properly, the leading vehicle must not change its driving regime, which is a better solution also in order to limit negative impacts on the traffic flow and avoid moving bottlenecks (as will be discussed in the following paragraphs). The optimization problem defined in this work is NP-hard which means that is not possible to find the best solution but only a local optimum solution that, still, implies fuel savings and lower emissions. It is worth noticing that this computational difficulty can be found in almost all the studies analyzed, found in bibliography, concerning an optimization model for truck platoons formation on a road network.

With the approach defined, the author performed simulations in a realistic scenario, considering a large part of the European network. The shortest routes for each vector, as functions of their origin-destination matrix, were calculated with the Open Source Routing Machine, the maximum speed was set to 80 km/h (a realistic value that poses some issues in the interaction with other trucks, as emerged in the European Truck Platooning Challenge [24]). Other assumed parameters were the tolerance margin for the arrival time, set to half an hour, and the minimum distance travelled in a platoon formation in order to compensate for the catch-up phase of the following vehicles, equal to 20 km. In the simulations, the impact of the surrounding traffic on the times needed to accomplish each maneuver were not considered. Fuel savings obtained this way were equal to 15,9% for the following vehicles in the ideal scenario in which the number of heavy vehicles able to join a platoon is high enough to maximize fuel-related benefits. Other simulation scenarios, more plausible, considered the Swedish road network on which 2.000 heavy vehicles have been planned to travel, this way a reduction of fuel consumption equal to 7,6% was achieved. In this work, no limit was imposed to the number of vehicles composing a platoon, also considering scenario in which twenty-eight trucks would join together, this hypothesis is hardly realistic, especially in the short term while the technology is still entering the market or without considering dedicated lanes. Other improvements for the optimization model that the author listed in the conclusions were, for example, the implementation of the drivers' rest times or the evaluation of the influence that the spatiotemporal distribution of the travels has on fuel savings. Also, delays in the platoon formation due to the surrounding traffic should be taken into account, as should happen for disaggregations imposed by cut-ins or ramp areas. Further studies about the presented model can concern the implementation of the rerouting function, in order to quantify the fuel savings linked to Truck Platooning for each proposed solution, or the acceptance of a platoon coordination system both by drivers and companies. In fact, the information received by the service provider will probably be indicative and not coercive, the platoons formation and consequent fuel savings will depend on the attitude of the drivers towards the received indications and the suggested speed and route.

K. Y. Liang, J. Mårtensson And K. H. Johansson, 2014. Fuel-saving potentials of platooning evaluated through sparse heavy-duty vehicle position data

Another paper that faces a similar subject is [36], in which 1.800 heavy vehicles travel on a 500 km^2 wide area. Also, another work from the same authors is cited: "When is it fuel efficient for a heavy-duty vehicle to catch up with a platoon?" where is stated that, generally, a heavy vehicle should accelerate to join a platoon if the distance from its destination is at least equal to 17 times the distance from the leading vehicle. In [36] the optimization problem has the objective to form the maximum feasible number of platoons, not to minimize fuel consumption as the one presented in [62]. Through map-matching, hypothesizing the path taken from each vehicle, three coordination schemes are evaluated in their ability to organize the catch-up of the following vehicles. Again, the strategies in which the leading vehicle decelerates are not considered. In order to avoid traffic perturbations and the creation of a bottleneck congestion behind the leading vehicle (that could hinder the formation of the whole platoon). The three coordination schemes considered in [36] are, then:

- catch-up coordination scheme
- departure coordination scheme
- transport coordination scheme

As in [62], the influence of the infrastructure and different mechanical characteristics among vehicles are not considered. The function assumed to quantify fuel consumption is as follow:

$$f = K_E \cdot v^2 \cdot d \cdot \varphi(d_r)$$

Where K_E is a constant that takes into account for energy conversion, v stands for speed, and d for the travelled distance. φ is equal to 0,9 for following vehicles, to 1 otherwise, which implies a 10% air drag reduction while travelling in a platoon formation (d_r is the kept headway). By the means of map matching, starting from the GPS vehicle position, a set of edges is defined on which it could be travelling. The actual edge is then determined on the basis of its orientation, the proximity to the GPS signal and the vehicle's driving direction. This is a simplified approach that still proves to be useful while studying a highway network. As a baseline scenario, in this article, the case of spontaneous platoon formations was chosen: once the itineraries were determined, an interpolation based on time determined which vehicles could form a platoon (i.e. keeping a reduced headway for at least two GPS measurements in a row, the speed difference not exceeding 5 km/h in order, for the two single trucks, to be considered a spontaneous platoon). From this baseline scenario the results mentioned above were derived: 1,2% spontaneous platooning that results in 0,07% fuel savings. Another parameter assumed in this study and also often found in literature is the distance of 100 m between trucks, below which a platoon is considered composed. The baseline scenario was, then, compared to the coordination schemes exposed below.

- catch up coordination: Every time a GPS measurement is recorded, the algorithm verifies if two trucks are close enough on the network for the catch up to be convenient (considering the acceleration needed to compose a platoon). The maximum speed for a single truck was set to 100 km/h while, for a platoon, this parameter dropped to 85 km/h. In order to assess the most economic and fuel-efficient solution, the model compares the speed profiles of the truck that catches up or keeps driving alone. It is not realistic to assume a heavy vehicle to increase its fuel consumption in order to form a platoon that will benefit other vehicles, potentially from a competing company;
- departure coordination: The departure time of the heavy vehicles composing the fleet are changed. In order to plan an encounter on the road network without the need to

accelerate and consume more. The binding condition is the arrival time for each vehicle that can't be delayed beyond a certain value just for the sake of platoon formation. The model identifies two vehicles with close origins and, comparing their route with a speed margin of 5 km/h, calculates fuel savings for both vehicles. A relevant feature of this coordination scheme is the possibility to consider, in the model, the resting times for the leading vehicles, breaks for refueling and early departures;

- transport coordination: In this approach the model doesn't consider the trucks GPS position but examines the road edges. If more than one heavy vehicle enters a road branch in a short time, a platoon can be formed. The authors employed a different fuel consumption model for this case:

$$f = K\mathrm{E} \cdot droad\,(1 + (N - 1)\,\varphi)\ if\ N \geq 2$$
$$f = K\mathrm{E} \cdot droad\ if\ N = 1$$

where N is the number of heavy vehicles that approaches the road edge, $K\mathrm{E}$ is a constant that accounts for energy conversion, φ = 0,9 accounts for the air drag reduction and $droad$ is the edge length;

- 1.773 heavy vehicles drove in the simulations on a 24-hour interval, during which 250÷350 heavy vehicles travelled simultaneously most of the time. Please refer to [36] for the whole set of results in the three coordination strategies.

For the catch-up coordination strategy, most of the benefits are achievable from vehicles closer than 5 km. It should be noted that, for the departure coordination solution, benefits arise much more than in the catch-up case (there is no need for further accelerations), but greater times are needed to reach the destinations. For the transport coordination scheme the results were recorded considering different time intervals under which the entries into the road branch became suitable for platoons formation (clearly, the greater this time interval, the lower the chance for a platoon to be composed in reality).

Reis V., Pereira R., Kanwat P., Assessing the potential of truck platooning in short distances: the case study of Portugal, 3th Interdisciplinary Conference on Production, Logistics and Traffic

In [106] a different approach is chosen. The authors, in fact, analyzed the opportunities that Truck Platooning could exploit on short haul segments. It is true, indeed, that Truck Platooning grants greater fuel savings during long travels and the bibliography mainly explored this field of research. However, in this work the feasibility of the system on short-distance routes is assessed, based on the following Portuguese case study. The largest Portuguese logistic operator's fleet has been considered, the company serves 250 destinations from seven warehouses (starting point for every considered truck). The origin-destination framework considered, then, doesn't allow routes longer than 350 kilometers, it is also worth noticing that the fleet of vehicles belongs both to MAN and IVECO which is one of the partners in the C-Roads Italy project. In order to assess how many of these kilometers can be travelled in a platoon formation, the authors applied a micro-simulation model using the Anylogic multimethod simulation software. The study is particularly relevant when is considered that "around 50% of freight transport demand is for distances up to 400 km[4]. Some assumptions were made while developing the model:

- the travel speed on highways is set to 80 km/h for trucks, while the maximum speed reached is 90 km/h (values similar to the bibliographical ones);
- platoons are formed only on highways, when feasible, for speed values higher than 50 km/h;
- platoons are formed only by 2 vehicles, with a headway of 15 m.

It is interesting how the authors coordinated the formation of platoons, when approaching a highway. The truck scans for other trucks travelling in the same direction and, if it finds one, waits for its arrival (without breaking the boundary that is its arrival time). If the truck doesn't find other vehicles with which to form a platoon, it continues along the highway and becomes available for other trucks approaching the highway.
From the results, a truck on the Portuguese network considered in [106] can drive within a platoon for 68% of the travelled distance (on average), this result is achieved without a fleet coordinator or departure time adjustments. The average fuel saving considered in the study is equal to 12,5% for both trucks in a platoon. On the basis of the monthly reference price for gas oil and the pricing of truck platooning equipment in 2014, the authors estimated a 2,5÷3 working years requirement to pay off the equipment.

2.5 Relevant maneuver and interaction with the surrounding traffic flow

In paragraph 2.4 what is necessary to assess the fuel consumption of a single platoon travelling in formation along a prescheduled route was described. In order to evaluate the real impacts of Truck Platooning on traffic efficiency, environment, safety and user acceptance, however, another subject must be considered. A truck platoon travelling on a public road will, certainly, face multiple challenges in its interaction with traditional, surrounding traffic. These challenges include its formation, disaggregation, lane changing maneuvers and overtaking maneuvers to name a few. These

[4] Eurostat, "Road freight transport statistics", 2012

interactions have a double effect, because they decrease benefits within the platoon and for the participating vehicles (resulting in a lower quantity of kilometers in which the platoon is feasible and in an increased number of maneuvers needed to keep the platoon together) but on the other hand they have an impact on the surrounding traffic flow, on its stability and on the driving smoothness for example. Another important aspect to consider is how the truck drivers performs these maneuvers, being part of something bigger, and how they perceive their presence into the platoon. It is worth citing [24], from the European Truck Platooning Challenge Experience: “Most truck drivers said that the chief difference between driving a truck platoon and driving a single truck, was awareness of being part of a single entity and the entity’s position in traffic”. Other interesting aspects emerged from the experience were, for example, how the lead truck driver had to be aware of the full length of the platoon before engaging a maneuver or how he had to anticipate events involving other road users. Moreover, it emerged how speed was a determining factor in the number of overtaking maneuvers from other road users or how dense traffic situations led to the dissolution of the platoon. In this paragraph the relevant existing literature is going to be reported to give an idea about what must be considered while modelling truck platooning and assessing fuel saving or other impacts. It doesn’t seem worth to dedicate a paragraph for the truck platoon lane changing maneuver, although the following considerations should be done. A truck platoon that wants to change lane needs an increased gap to merge with the flow, the leading vehicle driver should evaluate when this gap exists and then begin the lane changing maneuver with the assistance of technological equipment like the lane change assistant or the blind spot detection. In the short term, following vehicle drivers are going to keep the lateral control of their truck but the reduced headway will cause less visibility, this will increase the need to rely on technological equipment and sensors able to warn the driver in case of danger. Moreover, the lane changing maneuver can be one of the mitigating measures that can be adopted near ramp areas, for this solution to be feasible, though, it’s necessary that legislations regarding truck platooning won’t confine the platoon in the right lane (as happened in some countries during the European Truck Platooning Challenge). As will be elaborated in the last part of the Ex-Ante, some of the C-ITS Day 1 hold great potential in aiding the platoon during the lane changing in some scenarios and in minimizing the resulting perturbation on the surrounding traffic flow.

2.5.1 Platoon formation

This aspect can have both a huge or a reduced effect if the platoon is formed at the start of the journey or if it’s formed on the road. The latter hypothesis considers solutions that allows all properly equipped heavy vehicles to form or join a platoon met on the road (without exceeding the maximum allowed number of vehicles in a platoon), this is the solution most prone to interferences of the surrounding traffic. The first case, instead, is the one concerning mostly mono-brand platooning, namely the solution in which all the trucks composing a platoon are from the same brand and it’s impossible, for other heavy vehicles, to join the platoon on the road. Although, even when the platoon starts its journey already composed, it's not safe to assume that it will not decompose on the road when facing ramps, cut-ins, bridges or tunnels. This means that even mono-brand platoons must consider their recomposition along the route. When the drivers of two or more heavy vehicles wants to form a platoon, they must reduce the distance between them until the desired headway is achieved. This can be done without delays if there are no other vehicles between them, generally when the density of the surrounding traffic is low and the conditions are of free flow on the road. When there are vehicles between them, the following vehicle must wait until that vehicle has overtaken the leading one or changed lane, freeing the space to move closer. This means that the intruding vehicles must be able to perform a lane change maneuver therefore, so, there must be the gap on the other lane for it to leave the first lane. More congested is the road branch, more time is needed for the intruding vehicle to find the gap and bigger is the delay in the platoon formation. This implies less kilometers driven in formation for each truck and also an increased number of accelerations and decelerations needed to move closer and to finally form the platoon. Moreover, the more the flow is congested, the more the CACC prove itself useful when engaged. It's important to note that an optimization model that precisely accounts for those delays still doesn't seem to exist in literature, an optimization model is the tool used by a potential service provider in charge of the coordination of the platooning fleet.

Liang, K., Van De Hoef, S., Terelius, H., Turri, V., Besselink, B., Mårtensson, J. And Johansson, K.H., 2016. Networked control challenges in collaborative road freight transport.

An important article to cite about this subject is [41], where the automatic formation of vehicle platoons on a Swedish highway is analyzed, considering both the coordination strategies and the potential delays caused by the surrounding traffic flow. The decision to form a platoon is bound to the computation of the fuel-optimal formation maneuvers and their associated cost, therefore in this paragraph the authors' approach concerning the platoon formations will be examined. An optimal merge point on the road is determined as:

$$s_m = s_s \frac{v_2}{v_2 - v_1}$$

Where s_s is the initial distance between the two vehicles once they are on the same road segment, v_1 is the leading vehicle's speed and v_2 is the following vehicle's speed.

A point s_c exists, beyond which the platoon formation is no more fuel efficient when compared to the driving alone situation. This point allows to evaluate the delays caused by the surrounding traffic that can delay the platoon formation so much that the fuel reduction is no more worth the fuel consumption needed to the following vehicle to accelerate and reach the leading one. This point is calculated through the following equation, proposed by the authors as:

$$J = v_1^2(s_m - s_s)\varphi_1 + v_2^2 s_m \varphi_2 + v_p^2(s_f - s_m)\varphi_p = total\ fuel\ cost\ for\ reaching\ s_f$$

Where s_f is the point beyond which the platoon dissolves, φ_1, φ_2 are air drag coefficients and φ_p is the reduced air drag coefficient obtained from the following vehicle while in platoon formation. J is the fuel-associated cost. Clearly, speed values must be such as to allow both vehicles to reach their destination on time without exceeding speed limits on the road. Numerical simulations have been carried out by the authors, the most worth-noticing inputs assumed are:

- highway - number of lanes: 2
- maximum traffic flow: 2.200 veh/h/lane
- traffic flow densities simulated: 11-15-19 veh/km/lane
- v leading vehicle = 80 km/h
- v following vehicle = 90 km/h
- initial distance = 3 km
- headway = 30 m

The outputs achieved by the simulations are the delays in the platoon formation corresponding to the three levels of traffic densities simulated in [41]. The distance driven beyond s_m turns out to be increased respectively by 4%, 20% and 45%, the authors consider these delays caused by the low speed of the leading vehicle that creates a moving bottleneck effect among the other vehicles. These, then, queue between the two heavy vehicles and hinder the platoon formation. Then, in the last part of the article, an experiment carried on a public highway between Hallunda and Moraberg is described. For the specifications of this test please refer to the article, in this paragraph only the outcomes will be observed. The failed attempts in forming a platoon are caused by an almost congested traffic flow, by a high initial distance between the two trucks or by vehicles constantly queued after the leading vehicle. The latter situation is the least predictable one, there can be drivers on the road that have no intentions or reasons to overtake and change lane (the one with the lower driving aggressiveness), they can hinder completely the formation of the platoon. This issue can be tackled by the means of an increased communication between the platoon-oriented vehicles and the other ones, which can be achieved by an on-board signaling system like the one used during the European Truck Platooning Challenge [24] or the one examined in [7].

In [19] (*Deng, Q., 2016. Heavy-Duty Vehicle Platooning: Modeling and Analysis*) the author dedicates a paragraph to the influence of traffic on HDV platoon formation, considering the same traffic flow densities found in [41] (11-15-19 veh/lane/km) but different speed values of the leading vehicle (70 km/h, 75 km/h, 80 km/h). The ideal platoon formation time is then calculated from $t = \frac{d}{v_2 - v_1}$, where d is the initial distance between the two trucks, v_2 is the speed of the following vehicle and v_1 the speed of the leading one. From the simulations appears that, in light traffic, the delays are almost negligible (compared to the baseline values of 0,15h, 0,2h, 0,3h for v_1 equal to 70÷75÷80 km/h). In medium traffic the delay is equal to 58%, 45% and 21%, in heavy traffic, instead, those percentages become 83%, 72% and 48%. A relevant consideration to be done is that the simulations in this work seem to prove as stated above, that the deceleration of the leading vehicles doesn't reduce the time needed to form the platoon. It could seem counterintuitive, but the leading vehicle should not decelerate to let the following vehicle reach earlier, because a "lower speed of the first truck create a moving bottleneck and forces the following passenger cars to slow down or change lane. If passenger cars behind the front Heavy Duty Vehicle could not change lane because of large speed difference or not enough vehicle gap on the other lane, those passenger cars will keep driving behind the front Heavy Duty Vehicle and delay the platoon formation".

Saeednia M., Menendez M., 2017. A Consensus-Based Algorithm for Truck Platooning

In [96] the authors present an approach that considers the possibility to let the following vehicle accelerate or the leading one decelerate in order to form a platoon. The proposed hybrid approach includes an algorithm that can account also for modification of the platoon in response to environmental changes. The output of the given algorithm to the single truck is a set of optimal speed values, chosen to maximize utility (the platoon is formed if that solution results more fuel efficient than maintaining the current speed profile).

> "In this framework, a consensus-based platooning approach, which relies on real-time vehicle-to-vehicle communication, is developed for platooning trucks. To this aim, a platoon of trucks is modelled as a multi-agent system, in which the agents form a platoon autonomously by reaching a consensus among themselves. In such systems, the goal of the system is achieved in a cooperative manner and as a result of collaboration and cooperation among all involving agents."

This approach is one of the few ones that don't involve the presence of a service provider to coordinate the fleet, each approaching couple of trucks can form the platoon autonomously on the basis of this consensus-based algorithm that works iteratively in order to reach a set of speed values satisfactory for both trucks. The kept headway is based on the deceleration rate of the trucks and their braking distance, the utility for each truck is obtained considering its deviation from the planned speed profile, the disagreements between agents are calculated in terms of speed and separation errors, adequately weighted. For the equations on which the algorithm is based refer to [96]. The algorithm was evaluated through MATLAB simulations, notable inputs where the number of trucks (3÷10) and the minimum allowed headway (6 m). After the simulations, the authors stated that if the platoon can employ more time to form itself, a higher average speed is achieved by the involved trucks, this happens because the leading vehicle doesn't decelerate too much. This deceleration seems to be the most challenging characteristic of the consensus-based approach, generating moving bottlenecks as long as the leading vehicle decelerates. Another aspect that could hinder this solution concerns the little speed variation imposed by the algorithm at each iteration that could prove challenging for the drivers to follow as long as they remain in charge of the longitudinal control. On the other hand, this approach can guarantee high flexibility, letting the parameters such as speed and headway change at each iteration, based on traffic flow condition or other changes in the system.

2.5.2 Platoon disaggregation and other challenging maneuvers

The dissolution of a truck platoon can be achieved through deceleration of the following vehicles. In a two-vehicles platoon the following truck must brake or decelerate until the headway has reached 100 m (value from literature). If the platoon is composed by three vehicles, the following ones can start to decelerate together with the same deceleration value, or the last one can decelerate double the value of the middle one (considering a maximum value of -3 m/s^2 imposed by the comfort of the driver), in this way the time needed is reduced. In a four-truck platoon the disaggregation can be achieved splitting the platoon in two smaller platoons or letting each of the trucks leave the platoon formation. All those control strategies are in charge of the CACC and, in free flow conditions, can be evaluated on the basis of the time needed for the platoon to be dissolved. However, as for the merging maneuver, the deceleration capacity can be hindered by lack of space at the rear end of the platoon. Furthermore, this maneuver has certainly an impact on the surrounding traffic flow, imposing braking and reducing infrastructure's capacity. This issue was again analyzed in [19] (*Deng, Q., 2016. Heavy-Duty Vehicle Platooning: Modeling and Analysis*), where the impacts of the platoon disaggregation on traffic flow at highway off-ramp is investigated by simulations. In this case the traffic density considered is equal to 1.600 vehicles/h/lane and the platoon spacing policy considers a headway of 10 m. The CACC algorithm considered by the author calculates in 150 s the time needed for a five-truck platoon to dissolve (headway greater than 100 m). It is important to note that before reaching the off-ramp area, a distance of 100 m is considered safe for the disaggregation to have ended. While the impacts of Truck Platooning will be described later in this Ex-Ante, it is opportune to comment the outputs obtained in the simulations carried out in [19] about the off-ramp area (the baseline scenario considered by the author is the one where the platoon doesn't dissolve).

When the platoon does not disaggregate the average speed in the left lane decreases until the platoon approaches the off-ramp area. This is because the other road users have difficulties to find gaps to change lane, so they need to slow down and wait until the whole platoon has passed to be able to change lane and exit the road branch. Also, these maneuvers force the passenger cars on the right lane stop to let the vehicles from the left lane pass through and leave the branch. When the platoon disaggregates before entering the off-ramp area, instead, the average speed of the right lane decreases rapidly when the platoon starts to dissolve due to the deceleration of the platoon members like mentioned above. The platoon dissolution allows the vehicles on the left lane to find gaps to change lane and be ready to leave the road branch. This way the average speed recovers earlier compared to the baseline scenario, improving the traffic flow on the left lane. The increase in average speed on the left lane can be up to 8% compared with the no-disaggregation case.

Another scenario that could prove to be challenging for Truck Platooning is the cut-in one, resulting from the need for a single vehicle to take a ramp or to interrupt an overtaking maneuver. As mentioned above a long platoon represents a new challenge indeed for other road users. In the short term is easily predictable that many drivers will need to learn how to overtake a platoon composed by two or three trucks, considering the reduced headways and the inability to overtake the trucks one by one. As mentioned both in [24] and in [7], signaling the platoon can help the drivers to contextualize the situation earlier and better, reducing the number of interrupted maneuvers.

Cara I., Paardekooper J., The potential of applying machine learning for predicting cut-in behaviour of surrounding traffic for truck platooning safety

Another approach that aims to mitigate this problem is the one presented in [97] where a machine learning algorithm in the Support Vector Regression model is considered to improve the safety of truck platooning by predicting the behavior of passenger cars after a cut-in. This work focuses on safety, considering that the level of automation foreseen for Truck Platooning cannot be considered as fallback option when an external vehicle insert itself between two really close trucks.

> “Early prediction of the behavior of the car performing the cut-in will help to increase operational safety, because the controllers can use this additional information to anticipate the behavior of the car, which is especially important in case the V2V communication fails.”

This work holds an added value being based on naturalistic driving data part of the TNO Streetwise scenario database. The considered scenario is the highway one, the cut-in is defined as the moment in which the target car crosses the lane marker, starting from this moment the behavior of the vehicle is followed for 4 seconds (the maximum prediction horizon of the algorithm). The designed algorithm is compared to the baseline scenario where the on-board system of the truck considers the speed of the intruding vehicle to stay constant (which is often true, however the outliers are the most relevant in terms of safety). The forecasting strategies considered in the machine learning problem are four: direct forecast, recursive forecast, multiple-output forecast and direct-recursive hybrid forecast. Through different experiments the authors determined which one of the above is the best suited for the cut-in problem: the optimized direct recursive hybrid forecast (Support Vector Regression – dr-SVR) that outperforms the others and the baseline in terms of longitudinal and lateral distance between vehicles, speed and acceleration with a prediction horizon of 2 seconds. To give some of the experimental results as an example: "After 4 seconds, the error of the dr-SVR prediction in the longitudinal distance is 1,5 m, in the lateral distance 0,25 m, in the longitudinal speed 0,05 m/s and in the acceleration 0,15 m/s^2.

Gheorghiu, A., Iordache, V. And Cormos, A., 2017. Cooperative Communication Network for Adaptive Truck Platooning

Still another approach presented to facilitate the overtaking maneuver is the one in [85] which exploit the possibilities granted by V2V and V2I communications. One of the factors limiting the maximum number of trucks forming a platoon is the difficulty of overtaking for other road users. The strategy adopted by the authors to mitigate the risks and ease the maneuver accounts for the platoon to dynamically change the headway held by the trucks, allowing the convoy to break into two smaller platoons and leave a gap large enough for the overtaking vehicle to fit in and perform the maneuver in several steps. The scenario considered in this work is the one where every vehicle on the road is able to communicate through V2X communications, this implies a time horizon more advanced than 2020 (which is the Truck Platooning implementation one). Therefore, in order to define the headway value, the vehicles in formation detect the presence of other surrounding vehicles, minimizing the gap while in light traffic. As soon as the detected traffic density reach certain values, the headway should increase without exceeding a certain value (beyond which the numbers of cut-ins becomes so big it hinders the platoon conservation, this value is yet to be univocally determined and, as stated in previous paragraphs, strongly depends on the regional behavior and on the level of driver aggressiveness on the road). The platoon must dissolve when a vehicle cuts-in to avoid situations in which the platoon communication stands still but there are communication delays which could prove to be dangerous, also, this way the unpredictability of the intruding vehicle is considered.

For this approach to work, every following vehicle must be equipped so that it can become leading vehicle, besides the truck driver must be warned enough time in advance to be able to retake control of his vehicle. The authors, then, applied the defined dynamic headway strategy defined to tackle the issues of a "wall of trucks" near the off-ramp area that could hinder the exit of other vehicles. Other works regarding ramp areas and Truck Platooning are going to be examined in a dedicated paragraph, this comment about the approach presented in [85] simply brings the subject forward. In the off-ramp scenario it is possible for a vehicle that must take the exit ramp to communicate this need to the truck platoon traveling on the first lane. The position of this vehicle must be broadcasted to the platoon with extreme precision, though, this means that the position given by the GPS system alone could be not precise enough. For the platoon to open at the right point, indeed, a reference system validated through V2I communication is required (the authors considered an RSU at each ramp area).

For this system to function properly it is essential that the information travel with sufficient speed, so that the platoon can separate itself and create the intended gap for the vehicle to intrude the platoon and take the ramp. There is, therefore, a minimum distance to which the communication between platoon and the external vehicle must occur and this distance must be bigger than the one that separates the platoon from the ramp. The authors considered the distance as:

$$d = l_{el} + v_{pt}\left(t_{gap} + t_{in}\right) + d_{syn} + v_{ov} * t_{COM}$$

Where l_{el} is the length of the exit lane, v_{pt} is the platoon driving speed that the intruding vehicle has to reach, t_{in} is the time needed by the intruding vehicle to occupy the gap, d_{syn} is the distance it needs to decelerate from is initial speed v_{ov} to v_{pt}, t_{COM} is the time required for the information exchange to happen and t_{gap} is the time that the platoon needs to create the sufficient gap. In this work, the influence of the surrounding traffic is neglected as well, in order to adopt this kind of solution the impacts of the characteristics of the road and of the surrounding traffic flow should be assessed. Other factors on which the dynamic headway value depends are the intruding vehicle's length, the safe distance and the trucks maximum deceleration. The minimum distance necessary for the maneuver to take place is calculated by the authors using the following equation:

$$D > d = v_{ov} * t_{COM} + \frac{v_{OV} * v_{pt} + v_{pt}^2}{a_{brv}} + v_{pt} * \left(t_{sig} + \frac{w_l}{v_{lat}} + \sqrt{\frac{2(l_{ov} + 2d_s)}{a_{brt}}}\right) + l_{el}$$

Where d_s is the safe distance between the intruding vehicle and the trucks, a_{brt} the maximum deceleration, l_{ov} the intruding vehicle length, w_l the lane width and t_{sig} the time needed to signal the lane change intention. Using this formula, the truck platoon can calculate if the remaining distance before the ramps is enough or if the lane change request must be rejected and the vehicle must wait the next off-ramp.

The overtaking maneuver can also be started from the truck platoon to surpass slower vehicles on the right lane. This possibility is not straightforward as proved during the European Truck Platooning Challenge (Belgium, for example, confined truck platooning to the right lane, while the Dutch had a general ban on overtaking, which comes down to the same thing [24]). The legal framework is, indeed, an extremely important factor and some countries could decide to forbid platooned driving on different lanes than the first one. About this issue an interesting statement is made in [105]: “Measures or guidance to determine what happens when a convoy/platoon encounters a slower moving vehicle in lane 1. To avoid the road train’s overtaking maneuver reducing the motorway down to a single carriageway for potentially a significant time/distance, the road train should not be permitted to overtake a vehicle unless it is travelling slower than a particular speed (e.g., 40-50 mph). The actual value should be determined by the amount of time the overtaking maneuver takes. This will be affected by the size of the road train, the speed of the slower vehicle, and the speed of the road train. At a specific level of congestion this should cease to apply.”

2.6 Truck Platooning & Infrastructure

One of the most relevant benefits tied to Truck Platooning is the possibility of implementing the system without the need for big investments to adapt the infrastructure. This allows to shorten the time horizon on which the market entrance and Truck Platooning presence on public roads can be planned, besides no additional space for new roads is needed to increase capacity, making this solution much more attractive from an economic point of view. However, it must be verified that, for the road segments on which truck platoons will drive, the infrastructure is able to ensure safety for each of the road users.

> “We also need to pay attention to the infrastructure. In particular it is bridges in a state of disrepair, a lack of LTE coverage, poor road markings as well as heavy traffic and traffic jams that hinder the optimum use of platooning considerably” Martin Zeilinger – Head of Advance Development at Daimler Trucks

As already stated, the most critical points for truck platooning are ramps, roundabouts, bridges and tunnels. Also, it should be studied how guardrails perform in the most critical scenario concerning a platoon of trucks. Another important subject that concerns the infrastructure is the allocation of one lane on a freight corridor, even for a few hours a day. Among these, ramp areas are the most troublesome and many approaches have been proposed in literature, in this paragraph the most representative ones will be present. For example, during the European Truck Platooning Challenge the platoons were dissolved before ramp areas and, from the surveys submitted to the drivers, emerged how ramps were perceived as one of the most critical point along the route. Besides, it was concluded that headways lower than 0,8 s weren’t enough to prevent other vehicles entering the road branch from cut-in. Furthermore, two of the interviewed drivers stated how short German ramps were and how they didn’t believe that they could accommodate an entire platoon. Near ramp areas every drive had to be aware of being part of a bigger system, taking also into account the position of the other vehicles on the road and of potential trucks behind the platoon (from the surveys also emerged how the interaction with other trucks resulted often more complex than the one with cars).

Tabibi, M. Design and Control of Automated Truck Traffic at Motorway Ramps

In [58], a study being part of the Dutch program TRAIL, the possibility of a reserved lane for automated trucks on the European freight corridors is analyzed. In that scenario the author confronts the issues about ramp areas, defining what is the best lane to reserve that holds major benefits on traffic efficiency and safety. This thesis is not focused only on truck platooning but is worth analyzing, being one of the few works in literature that consider the reservation of a lane to automation (where the headway is still reduced by the means of technological equipment). The automatic driving system assumed, in fact, is slightly different from what appears to be the most likely solution for Truck Platooning implementation, in this case the automated heavy vehicles are controlled by a Traffic Control Center that can impose speed values, kept headway and routes on the basis of the results of a traffic optimization model (a PSP can only give indications about these parameters, instead). Despite the Traffic Control Centre's role, in [58], drivers are still expected to be present on each truck to ensure adequate safety levels. The thesis evaluates the benefits that the automation of a part of the traffic flow can bring to the Traffic Efficiency in the particularly critical segments of the infrastructure, such as on and off-ramps. The author cites Minderhoud and Hansen that showed how automatic vehicles, whose headway is controlled by an external figure, are able to increase safety in the flow downstream an on-ramp, the capacity and the average speed of the flow approaching the narrowing of carriageway

The reservation of a lane to automation (or, in the present case, to truck platoons) implies benefits on the traffic efficiency when the CACC market penetration exceed a certain percentage and when the goods transportation vehicles are a relevant portion of the traffic flow. This solution must face some challenges, though. For example, the issue of a truck entering the main branch from the on-ramp and wishing to enter the reserved lane represents a disturbance in the traffic flow and can face safety critical situations. Which one of the lanes must be allocated to automation influences greatly both aspects, through a bibliographical study the author concluded that solutions considering "transition lanes" in which the vehicles could shift from manual to automated (or semi-automated) driving would be unsafe for the traditional vehicles, in the event of a system failure in heavy vehicles during the transit phase. The scenario considered by the author was a three-lane segment passing an on-ramp area, where the first lane (the right one) or the third lane (the left one) could be allocated to automated driving, the choice of the reserved lane proved to significantly impact the traffic flow. If the third lane is reserved, the different dynamics of the automated traffic impose fly-overs or ramp metering strategies on the main branch. Clearly that solution would be sub-optimal in term of traffic efficiency, for this reason the author focused on the impacts on the traffic flow resulting from the

allocation of the first lane to automation. It is important to note that, despite the work being focused on an automated lane, many of the theoretical results can be projected on the Truck Platooning scenario, the main difference being the lateral control in the hands of the drivers. The optimization model used to assess the reserved lane impacts was implemented on the SiMoNe software (Minderhoud M.M. Technical specification of SiMoNe, Delft University of Technology, Delft. 2001).
Inevitably, reserving one lane to trucks implies a degradation in traffic flow for the other road users that must be validated by a high percentage of trucks on the road and a cost-benefit analysis. The configuration in the figure above is considered by the author the best one regarding entrances and exits of heavy vehicles on the reserved lane where the flow is hindered by the incoming traditional vehicles, though. Reserving the third lane, on the other hand, would make heavy vehicles hinder the flow of the traditional ones, a less safe scenario according to the author. Through the software SiMoNe, the reserved lane scenarios were compared to the baseline one and to a scenario in which no lane was reserved but heavy vehicles were confined on the first lane. The road segment on which the simulations were carried out included both one off-ramp and one on-ramp, every heavy vehicle was considered equipped for the autonomous driving. Traffic density was equal to 4.000 veh/h on the main branch (of which 5%, 10%, 15%, 20% and 25% heavy vehicles) and to 1.000 veh/h on the on-ramp (of which 5%, 10%, 20% and 40% heavy vehicles). Every simulation lasted 4 hours and accounted for around 20.000 vehicles. Heavy vehicles on the off-ramp were assumed equal to 10% of the exiting flow. The outputs obtained from the model are:

- queue length
- traffic flow
- average energy consumption – number of accelerations and decelerations
- Time To Collision (TTC)

These outputs depend on the ramp flows.

The capacity on the main branch wasn't reached for any value of the heavy vehicles percentage on the on-ramp, up to the maximum simulated one of 25%. The worst scenario in terms of capacity and congestion seems to be the one with few heavy vehicles on the main branch (5%) and, at the same time, trucks on the on-ramp equal to 40% of the traffic flow. This situation, in fact, involves the maximum number of interferences between heavy vehicles and other road users. Simulations showed that there is no scenario that, in general, obtains a capacity higher than the baseline one. Moreover, the author concluded that with a scarce number of heavy vehicles on the on-ramp (5%), there is no big difference in performances between the baseline scenario and the reserved first lane one. These considerations are based on travel time and traffic flow. Regarding the number of accelerations and decelerations, an increasing number of trucks on the main branch makes all the scenarios converge from the energy consumption point of view. When this presence is low (5%), all the reserved lane scenarios gave back an increased number of accelerations and decelerations, instead. When considering energy consumption, simulations show how the best scenario is the one where no lane is reserved and heavy vehicles are confined on the first lane. It is worth noticing that all these evaluations are extremely variable depending on the percentage of heavy vehicles considered, for a comprehensive analysis of all the cases examined please refer to [58]. To assess safety among the different scenarios, TTC was used as performance indicator and compared. The critical value chosen by the author to identify unsafe scenarios is equal to 1,5 s[5]. Despite this evaluation not being tailored on Truck Platooning, the inputs assumed can be taken as a reference to analyze the feasibility of a reserved first lane. Another relevant value for the TTC is 3 s, below which the Forward Collision Warning can warn the driver or the system about the need of an emergency braking [94].

Other simulations were carried out in [58], exchanging the percentages between the on-ramp and the off-ramp, this way conclusions were drawn about impacts on traffic efficiency. The reserved first lane scenario rarely reached the capacity of the main branch, the only conflicts arose when a relevant flow of traditional vehicles exiting the main branch hindered the heavy vehicles driving on the reserved lane. Besides, the results showed how a higher percentage of heavy vehicles in the main flow causes more similar travel times between trucks and the traditional traffic. A value of 20% of trucks on the main branch in the first reserved lane scenario gives back output similar to the baseline scenario ones. Regarding energy consumption, results showed that a first reserved lane reaches performance levels similar to the other scenarios for a percentage of trucks on the main flow equal to 25%. The author highlighted how, considering accelerations and decelerations to assess the environmental impacts, traditional traffic should be considered too. Another consideration worth noticing is that the feasibility of V2I communications and dynamic lane allocation should be evaluated, reserving lanes to heavy vehicles and semi-automated driving only during the hours in which the traffic flow is lighter. Dynamic allocation is able to ensure an unchanged outflow for traditional traffic during the peak hours and a greater flexibility, for example, during night hours. Generally speaking, greater flexibility proves to be beneficial in almost all aspects related to Truck Platooning (e.g. the headway, the reserved lane or the number of vehicles in formation). Separating traffic flows during night hours allows to consider the deployment of longer platoons and narrow headways, the benefits deriving from this type of solution have not yet been analyzed though. The limits that the system can reach under the hypothesis of reserved lane or night driving should be explored.

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[5] Hoogendoorn and Minderhoud (2001)

Once the two sets of simulations were carried out, the author presented some considerations.
The implementation of a reserved lane for automated freight transportation is not considered advisable when the number of heavy vehicles in the traffic flow is lesser than 10%. Furthermore, reserving the third lane is a sub-optimal solution if there are no ramp-metering systems. A reserved right lane, on the other hand, is a competitive solution in most scenarios when the number of trucks in the main flow exceeds 20% and the number of heavy vehicles on ramps results above 150-200 per hour.
Modeling a reserved lane, the following parameters have been assumed:

- $s_{int\ ra}$ = headway kept by platooned trucks = 10 m
- $s_{int\ er}$ = distance between platoons = 150 m
- L = average truck length = 14 m
- N = number of vehicles forming a platoon = 10
- v_{plat} = speed of the platoon = 88 km/h
- cap = capacity of an uninterrupted flow on the reserved lane

$$cap = \frac{3600 * N}{s_{int\ ra}(N-1) + L * N + s_{int\ er}} v_{plat} = 2300 \frac{trucks}{h}$$

This obtained value is theoretical and doesn't account for entry and exit maneuvers, nonetheless, the increase in capacity is about 53% on the reserved lane. To assess the impact of on and off-ramps on the flow of truck platoons, a road segment in which the first lane was allocated to truck platooning was simulated through SiMoNe. To reach the road capacity on the main branch the software generated high mixed flows both on the main branch and on the ramp (on which a percentage of 10% was assumed for trucks). All trucks were again assumed to be equipped with the same level of automation, the baseline adopted was the scenario where no truck forms a platoon on the dedicated lane. The following inputs were varied through the simulations: maximum number of vehicles in a platoon, initial number of vehicles in a platoon, headway, distance among platoons, speed, maximum acceleration and deceleration for trucks, average truck length. Again, for all the numerical results, refer to [58].
The following are some significant results:

- as the maximum number of vehicles forming a platoon changes, no scenario showed higher traffic efficiency than the baseline one;
- as the maximum number of vehicles forming a platoon increases, every performance indicator improves;
- the truck platooning scenario shows a lower number of accelerations and decelerations, as well as a higher time to collision (TTC);

- as the number of vehicles in formation before reaching the dedicated lane goes from 2 to 5, the capacity increases by 10%;
- regarding capacity, travel time and TTC the optimal number of vehicles forming a platoon is 5;
- the optimal headway value is function of the car volume on the on-ramp, the road section layout and the safety level required;
- the best performances are obtained with 50 m between platoons on the dedicated lane
- a platoon speed value equal to 85 km/h returns 21% less safety critical situations (TTC < 1,5 s) than the scenario in which the speed is equal to 55 km/h. This is imputable to an increased homogeneity between the trucks flow and the traditional flow;
- varying the value of accelerations and decelerations between 1 and 4 m/s^2 returns the same outputs as the 2 m/s^2 scenario;
- platoon disaggregation before the ramp area results in a capacity increase by 7% compared to the baseline one and by 15% compared to the scenario that doesn't consider the dissolution. This result is worth noticing because in literature the disaggregation approach is the most adopted to face ramp issues and proves to be the best solution in [58];
- platoon formation downstream an on-ramp can be a safety critical scenario (TTC < 1,5 s) because of the produced shockwaves that could propagate from the merging point upstream until the ramp area.

A set of simulations was also carried out for off-ramp areas with a percentage of exiting vehicles equal to 20%. The following considerations were made from the author:

- as the maximum number of vehicles forming a platoon changes, no scenario showed higher Traffic Efficiency, safety or better energy consumption than the baseline one
- as the number of vehicles in formation before reaching the dedicated lane increases, better capacity and safety performances are achieved;
- a platoon formed by 5 vehicles perform almost as the baseline scenario as long as capacity is concerned but involves higher travel times, earlier congestion and increased number of accelerations. Moreover, the number of safety critical scenario increases;
- the number of accelerations and decelerations for the vehicles on the main branch increase in the truck platooning scenarios at off-ramp areas. This could be imputable to the need to find a gap wide enough to exit through the off-ramp;

- the same considerations about platoons' speed made for the on-ramp case can be repeated for the off-ramp case. There were no performance improvements compared to the baseline scenario;
- the same considerations about accelerations and decelerations made for the on-ramp case can be repeated for the off-ramp case;
- platoon dissolution before the off-ramp area results in improved performances. The average number of accelerations and deceleration compared to the baseline scenario is halved.

Lastly, the author while considering the possible approaches to decrease the number of safety critical scenarios, mentions the Intelligent Speed Adaption (ISA) system to diminish the risks arising during the interactions between traditional and semi-automated traffic flow. The ISA, in fact, can impose decelerations on the vehicles approaching the off-ramp area, this solution doesn't seem feasible in the short term (being bound to high market penetration to function properly), though.

The author, then, deals with another subject: buffer areas. A buffer area is a bigger section of the infrastructure in which one or more lanes provide additional space for queued vehicles. In this way the density of the queue is increased and capacity is added through new space. Such an element is interesting for the possibility of creating lanes dedicated to specific user groups such as automated and semi-automated trucks, below some generic considerations from the author are listed.

The presence of a buffer area allows to regulate the input flow approaching the bottleneck, through the presence of traffic light lanterns. If the flow is composed only of traditional vehicles the buffer area is only able to absorb the queue propagation and doesn't avoid congestion. If the traffic is composed also of automated trucks, instead, it is possible to reduce the level of congestion near the ramps. The author in the study hypothesized, in fact, a mainline buffer able to control, through central coordination, the flow of heavy vehicles just before on ramps and limit the interactions with traditional vehicles that were the main problems analyzed in the first part of his thesis. Besides, inside the mainline buffer, truck platoons could be composed and headways could be reduced, in this part of his work the author explicitly refers to Truck Platooning and to the possibility of trucks to rearrange themselves in order to couple with the ones with the same destination. This kind of solution surely offers a different approach for the issue of ramp areas but involves increased costs and needs additional land space that could be used for social activities, therefore is not in line with the implementation strategies shared by the majority of the involved stakeholders. Moreover, an increased rigidity in the merging maneuvers can drastically limit the benefits deriving from Truck Platooning, especially if few, predefined merging points are identified.

The conclusions of the author are then reported at the end of his thesis work. The use of automated or semi-automated trucks and a careful optimization model can lead to an increase in capacity at off-ramps (up to 18%), a 10% reduction in travel time for all vehicles and a 40% reduction in accelerations and decelerations. Another benefit of truck platooning at off-ramp area is the higher set of TTC values. For the on-ramps, the benefits resulted in fewer accelerations and decelerations (20%) and higher TTCs, rather than an increase in capacity. An interesting idea that deserves to be analyzed concerns the night hours in which some of the limitations related to safety can be relaxed depending on the reductions in traffic flows. Another consideration of the author provides a further starting point, the modeling of one or two ramps with the level of detail adopted in this work is not possible for the entire road network, this means that it is not possible to apply this model to obtain impacts on the capacity, on the emissions or on safety resulting from the implementation of the reserved lane on the entire portion of the infrastructure. Moreover, the definition of cost-benefit analyses and risk analyses for all the possible scenarios regarding dedicated lanes should be evaluated. Further definition of input parameters (such as aerodynamic drag or fuel savings) is needed to assess impacts more accurately. Other outputs to considered in future modelling works could be the Average Waiting Time for traditional vehicles and for trucks.

Smith, D., A., 2016. Modeling and understanding the implications of future truck technology scenarios for performance-based freight corridor planning

There is another work that considers the dedicated lane approach while assessing impacts of Truck Platooning on a freight corridor [86]. The authoress's purpose was to develop a simulation model and a performance measurement tool able to consider the Truck Platooning technology. 14 scenarios have been analyzed along the Georgia corridor that includes the I-85 and the I-285 roads, Truck Platooning impacts are assessed from an economic, security, congestion and emissions, the level of automation considered seems to settle between the L3 and L4 levels (SAE Classification [61]). The system, in fact, manages both lateral and longitudinal control and the following vehicles could be driverless. The considered and compared scenarios involve both the dedicated lane solution for truck platooning and mixed scenarios where platoons interact with traditional traffic flow. The road network was loaded using an O-D matrix from 2012 and provided by FAF (Freight Analysis Framework), then, through consecutive iterations, the loads on each branch of the network were determined and projected on a 2040 time horizon (the 2040 value was chosen firstly based on data availability). Once defined the road network state and the circulating traffic flows, the 14 scenarios were set, 12 of which considered truck platoons on the roads. Some of the scenarios contemplate a dedicated lane on carefully chosen sections to maximize the involved benefits, please refer to [86] for the results regarding dedicated lanes built from scratch, this kind of solution involves huge investments and land usage so is not analyzed further.

> "The topic of autonomous vehicles has been discussed for some time now. While the question in the past has focused on "if", as in "if this technology will become a reality", the question has now shifted to "when""

Once defined the evaluation scenarios, the authoress set the minimum distance a platoon must drive in formation equal to 322 km, under this value the involved fuel savings aren't judged worth the effort to form a platoon. This value is really high for European standards and must be read in comparison to the American reality. The simulations considered three or five trucks in a platoon, each with a driver on board, the economic potential of the highest levels of automation are evaluated only in subsequent sensitivity analyses. As in other works, every truck was considered equipped for truck platooning and is hypothesized that every heavy vehicle that drives more than 322 km joins a platoon, when possible. An important input often neglected in literature but defined in this work is the PCE (Passenger car equivalents) for the heavy vehicles driving in platoon formation, the value was determined multiplying the single truck PCE for 0,46, value based on the smaller space occupied while platooning compared to the truck traditional driving (as estimated, for example, in [35]). The following outputs have been chosen to design the performance measurement tool:

- number of truck-involved crashes
- number of truck-involved crashes per vehicle-miles-travelled
- truck operating costs
- congestion cost for trucking industry
- peak hour travel time in minutes
- travel time index: ratio between peak hour travel time and free flow travel time
- travel time difference between ATP (autonomous truck platooning) trucks and unequipped trucks
- total truck emissions during peak hour
- trucking industry percent contribution to total emissions
- percent difference in estimated emissions from an n-truck platoon and emissions from n trucks traveling separately

The first and second outputs couldn't be quantitatively assessed through simulations because the authoress didn't judge sufficient the bibliography about safety related data for truck platooning in mixed traffic. Operating costs were quantitatively assessed, instead, and proved to be subject to congestion levels, truck mechanical features and to the level of technology equipped. The economic

benefits resulted from the simulations and tied to fuel savings and a dedicated lane are equal to 8% for a single unit truck and to 9% for a tractor plus semitrailer combination (values obtained without considering the technology costs), the latter are, in fact, lighter and more energy efficient. In assessing congestion related costs, the authoress used the parameter "time value" to monetize delays. Thus, in the truck platoons reserved lane scenarios, the congestion related costs decreased by 36% for tractor plus semitrailer combinations and by 43% for single unit trucks. The travel time index (defined as the ratio between travel time in the peak hour and the one in free flow conditions) differed by 80% from the values calculated for traditional freight transport, instead.
Another result from the simulations worth noticing is the change in emissions between the truck platooning scenarios and the ones with the same number of heavy vehicles driving by themselves. When no reserved lane is considered, the percentage reduction in emissions results equal to 2,4% for single truck units and to 9,5% for tractor plus semitrailer combinations. If a dedicated lane is allocated, the single truck unit emissions drop by 8,3%, instead. For the tractor plus semitrailer combinations the simulation shows a strong $PM_{2,5}$ reduction (8,7%), while for NO_x and CO_2 emissions the percentages are 3,7% and 2,6%, respectively. The authoress notes that the introduction of dedicated lanes may favour an intermodal shift from the rail system that is difficult to quantify a priori and involves increased values of heavy traffic and linked emissions. This aspect wasn't analyzed further and is one of the limitations listed in the conclusions, together with the uncertainties related to the technology development and the ones linked to the input parameters values projected on different time horizons. Another hypothesis whose implications should be explored is the lack of other cooperative or automated vehicles in the simulations despite their deployment being foreseen on the same time horizons as Truck Platooning. A dynamic allocation of lanes in different hours of the day could be a more realistic approach but the scarcity of available data has prevented the simulation of this kind of scenario. Further studies considered useful in the conclusions concern the evaluation of a dedicated lane costs and their addition among the model inputs and the simulation on a broader road network that could provide more general results. Ramp interactions were also completely ignored, to consider them and the interactions with traditional traffic, a joint use of the model with a microsimulation software is considered. An additional research question concerns the hypothesis of platoons formed by electrically powered heavy vehicles instead of fossil fuel powered ones. All these insights can potentially change the cost-benefit analysis results and the other outputs from the model.

H. Ramezani, S. E. Shladover, X. Lu, F. Chou, 2018. Microsimulation Framework to Explore Impact of Truck Platooning on Traffic Operation and Energy Consumption: Development and Case Study [119]

In this work a micro-simulation model is used to evaluate the impact of CACC-equipped heavy trucks driving on a freeway with manually driven cars. The results obtained concerned both the energy consumption for the trucks and the overall traffic flow and the impact on the average speed on the corridor I-710 Northbound. The platoons considered for the evaluation are composed by three trucks: in this way it was possible, for the authors, to calibrate their model on data resulting from the experiment [116] and to adapt the Motor Vehicle Emission Simulator (MOVES) to the Truck Platooning reality. An important hypothesis that should be highlighted is that, in the simulations, 100% of the driving trucks were considered equipped with the CACC system.

To assess the impacts of the truck platoons on the surrounding traffic flow (and vice-versa), first following and leading trucks were defined: a truck is considered as following vehicle if the time gap between itself and the preceding truck is shorter than 2,5 s; moreover, a platoon cannot be composed by more than 5 trucks including the leader. If a truck is not a following vehicle is considered a leading vehicle. Besides, the truck considered in the simulation is able to switch between Cruise Control, Adaptive Cruise Control and Cooperative Adaptive Cruise Control, depending on the preceding vehicle. The implemented car following models are reported as it follows, $a_{target}(t)$ is the value that the system (or the human driver) aim to reach:

- for a traditionally driven car:

$$a_{target}(t)\text{: } Max\ (b_f, Min(a_F(t), a_N(t), a_G(t)))$$

where b_f is the maximum braking rate, a_F is the acceleration rate to reach free flow speed, a_N is an acceleration rate based on the car following theory of G.F. Newell (2002) and a_G is a deceleration component presented by P.G. Gipps (1981), beyond a certain value of a_G the driver of the truck may switch back to manual mode to avoid uncomfortable decelerations.

- for the trucks driving with the CC, ACC or CACC engaged:

$$a_{target}(t)\text{: } Max\ (b_f, Min(a_F(t), a_{AUT}(t), a_G(t)))$$

where a_{AUT} is the acceleration rate for one of the three Cruise Control modes. When the CACC is engaged this parameter is equal to $a_{AUT}(t) = k_p e(t-1) + k_d \dot{e}(t-1)$ where $e(t-1)$ represents the error from the desired time gap: $e = d(t-1) - t_{des}^{CACC} v(t-1)$ with $d(t-1)$ equal to the distance in meter between the vehicles and v the truck speed. k_p and k_d are equal to 0,0074 s^{-2} and to 0,0805 s^{-1}, respectively, for the first following vehicle behind the leading one. For the other following vehicles these values become 0,0038 s^{-2} and 0,0650 s^{-1}.

As long as lateral control is concerned, trucks are restricted in the first lane to comply with the legal framework of the Californian state. In their interaction with the surrounding road users, the simulated trucks can create a gap for vehicles near ramp-areas only if are in the leading position, which means that no gap inside the platoon is formed to allow an external vehicle to cut-in. Nevertheless, should a cut-in occur, the model considers the following trucks able to interrupt the CACC communication and switch in ACC mode (these driving behavior were modelled by the authors through Aimsun).

Once defined this framework, the I-710 Northbound was studied, this corridor connects the Port of Long Beach to the Interstate highway system and is, therefore, travelled by a fair share of heavy vehicles (in a range of 10% – 19% of the overall traffic). When considering ramp areas, the most critical section is the one between Mileposts 2 and 3 which as three lanes and there are off and on-ramps closely spaced. On the section considered by the authors for the modeling work there were 11 mainline loop detectors which collected data during a Tuesday.

To determine the maximum acceleration rate of the considered trucks, the authors considered the weight-to-power ratio and the truck speed (on the basis of an NCHRP study about the heavy traffic on the interstate highways). Thus, the maximum acceleration resulted equal to 0,24 m/s^2 for speed values between ≈ 50 ÷ 65 km/h, to 0,15 m/s^2 for speed values between ≈ 65 ÷ 80 km/h and to 0,12 m/s^2 for speed values higher than 80 km/h. On the basis of the same NCHRP report, the authors considered an average maximum deceleration values equal to 0,18 g. A relevant value chosen by the authors is the desired time gaps chosen by the truck drivers while in platoon formation, equal to 1,2 s for 60% of the drivers and to 1,5 s for the remaining 40%. These values are rather high and are based solely on the psychological needs of the truck drivers (that surely are relevant but can be tailored to more efficient platoons with ad-hoc licenses and courses). When the ACC is engaged, the desired time gap is equal to 2 s in the model developed in [119].

To calibrate the traffic volumes simulated, the outputs of the loop detectors were confronted with the number of vehicles considered in the model (to have a good calibration, the authors considered the GEH index that accounts for both the traffic recorded by the detectors and the simulated value). Thus, the model was run and results were obtained:

- the VMT (Vehicle Mile Travelled) increased by 5,8% for trucks and by 0,7% for cars;
- the average speed increased by 19,3% for trucks and by 6,2% for cars;
- the truck flow rate increased in a range between 2,1% and 8,3%;
- the increase in speed is more relevant for the sections with the lowest average speed in the baseline scenario because the platooned trucks postponed the onset of congestion;
- the variability of the results suggests that some of the results could vary in a certain range, overall from the study it seems that having the whole fleet of trucks equipped with the CACC doesn’t affect negatively the mobility of the surrounding road users.

For a more complete dissertation of the results please refer to [119], it should be noted that in this work the performances of the different car following systems implemented in the simulations (CC, ACC, CACC) were evaluated.

> "The main reason for these improvements is that truck CACC reduced congestion near the beginning of the corridor, which improved mobility of passenger cars as well. In addition, truck CACC increased truck speeds in the uncongested conditions; thus, passenger cars which get stuck behind trucks or follow them could travel faster than in the Base condition"

On the basis of the results obtained from the simulations, the authors then assessed the energy consumption with a fleet composed by CACC-equipped trucks on the same corridor by integrating the micro-simulation model with the MOVES program. The first issue that the authors faced was the inability of the MOVES program to consider the aerodynamic effect of Truck Platooning, thus an adaptation of the approach was proposed in [119]. The MOVES model uses the instantaneous speed and acceleration values to estimate energy consumption on the basis of the Vehicle Specific Power for cars (the required tractive power to move a vehicle, normalized by mass) and of the Scaled Tractive Power for trucks. On the basis of the VSP or of the STP, different operating modes are defined in the MOVES model and, for each one, an energy rate is derived

To account for the aerodynamic benefits deriving from the Truck Platooning, one of the coefficients in the STP formula can be reduced (the ones that incorporates the drag coefficient). It is worth noticing that the re-calibration of this coefficient carried out from the authors in this work is based on the results of the experiment [116], as mentioned above. As highlighted by the authors, one of the limits of the MOVES approach is that the Operating Modes are discrete, thus if the change of the value of the coefficient that incorporates the drag coefficient isn't relevant enough, no differences in the energy consumption rate are obtained. To face this issue, the energy consumption rates in the previous figure were considered as mid-STP values and the remaining values were "(…) determined by interpolation or extrapolation".

The results concerning the lower fuel consumption are the following (energy consumption was normalized by VMT):

- energy consumption decreased by 3,05 % in average for CACC-equipped trucks;
- the average reduction in energy consumption due to the speed change was equal to 2,57%;
- the aerodynamic effect resulted in a reduction of energy consumption by 0,48% (and didn't vary over different runs).

Some hypothesis should be commented. First, the leading vehicle didn't enjoy a reduction in their fuel consumption (which isn't necessarily true but seems realistic with such wide time gaps).

Moreover, following vehicles both braking or stopped didn't enjoy energy savings (because in these phases the engine power is not employed). Leading vehicles and braking or stopped trucks accounted for 84,28% of truck-time-travelled, a rather high value that results from the lack of both a platoon formation strategy and a platoon cohesion strategy, as stated by the authors. Moreover, the results show how the energy savings is relevant for speed values higher than ≈ 56 km/h.

Bakermans B.A., Truck Platooning, Enablers, Barriers, Potential and Impacts. 2016

In [112] a similar time horizon (2020-2040) is adopted to evaluate Truck Platooning impacts on the modal shift from rail mode and inland waterway transport. This assessment has been carried out for three scenarios:

- considering only fuel savings due to air drag reduction;
- considering higher levels of automation (level 3 and 4);
- considering following vehicles travelling without drivers.

Once defined the savings related to each scenario for Truck Platooning, the Dutch freight database analysis was carried out to find the number of feasible truck platooning trips on the network. This number is needed to quantify the benefits related to Truck Platooning and to compare them to the other modal choices and evaluate the modal shift by the means of the BasGoed model (able to estimate future freight flows, i.e. 2020 and 2040, for different scenarios). To quantify fuel savings due to air drag reduction, the author employed the following equation:

$$S = \left(D_f - \frac{D_i}{v_l - v_f} * v_l\right) * FC * E$$

Where S represents the savings per kilometer (in litres), D_f is the trip distance of the leading truck, D_i is the initial distance between trucks, v_f and v_l are the speed values of the following and leading truck respectively, FC is the fuel consumption of a regular truck and E the effect of platooning on fuel consumption. The catch-up maneuver is carried out with v_f = 90 km/h and v_l = 80 km/h, too. The time loss of the leading truck due to the need to wait for the following one is considered too with the following equation:

$$D_{fmin} = \frac{VoT}{f * S}$$

Where D_{fmin} is the minimum number of kilometers to reach profit point, VoT the value of time for freight transport (in Netherlands), f the flow of trucks and S accounts for the fuel price.

> "A three trucks platoon has higher fuel consumption benefits, however due to a higher loss of time the minimum required platooning distance is earlier reached for a two trucks platoon. For longer distances a three-trucks platoon becomes more beneficial. This trend will increase for platoons with more than three trucks."

In the second scenario is assumed that driver tasks become less demanding and the drivers more productive, which also means that more kilometers could be covered between two breaks (changing the leading driver at the right moment). Hypothesizing that time in following trucks evolves twice as slow as in the leading truck, the distance travelled by a two trucks platoon results increased by 25%. When drivers are not needed in every truck (as in the third scenario) the operating cost drops and therefore the potential of truck platooning increases. Thus, on the basis of the freight database analysis and the heavy vehicles O-D matrix, the eligible trips for truck platooning are determined (which means that the time losses are compensated by savings due to platooning). An important assumption was made by the author while evaluating the eligible trips, the platoons could be formed only between trucks with the same origins and destinations. This results in a strong approximation because all the platoon that could be composed just for a part of the trip were neglected. This approximation surely contributed to the author's conclusion that truck platooning is probably not economically feasible when only fuel savings are considered and that cross-border platooning is not promising as national platooning. Nevertheless, these results deserve an in-depth analysis and future researches in order to assess how much the assumption made contributed to these peculiar outputs. Once defined the different Dutch Truck Platooning scenarios projected on different time horizons, the modal impacts of Truck Platooning were estimated on the basis of the system benefits compared to its competitive modes and through the Dutch transport model BasGoed. This model considers the most common parameters influencing the modal choice, such as cost, distance, time and volume, then compares the cost functions for each choice and selects the lower one. Only the air transport mode was not considered in this research.

The results showed that larger penetration rates lead to a larger modal shift and that savings in labor cost seem to impact more than fuel savings. It should be noted that an increased employment of Truck Platooning for freight transportation can lead governments to consider measures against the system, in order to foster modes not involving the road network.

Van Maarseveen S., 2017, Impacts of truck platooning at motorway on-ramps

In [102] the impact of Truck Platooning at on-ramp areas are analyzed concerning both Traffic Efficiency and Safety. In fact, the merging behavior of human drivers when approaching a truck platoon is still largely unknown. Besides, what are the best platooning strategies and configurations is still to define.

The author, then, conducted a literature review in order to explore different gap regulation strategies and car following models, then carried different simulations out, considering “a multi-anticipative Cooperative Adaptive Cruise Control (CACC) controller using a constant time gap strategy”.

$$a_{i,t}^{car-following} = k_s\left(s_{i,t} - s_{i,des,t}\right) + k_{\Delta v}R(s)\left(v_{i-1,t} - v_{i,t}\right) + k_a a_{i-1,t}$$

Where $a_{i,t}^{car-following}$ is the desired acceleration of the following vehicle, $s_{i,t} - s_{i,des,t}$ the difference between the desired spatial gap and the held one, $a_{i-1,t}$ the acceleration of the leading vehicle communicated through the Dedicated Short Range Communication and R(s) is a collision avoidance function. k_s, $k_{\Delta v}$ and k_a are control parameters.

It is important to highlight that in this modeling work both longitudinal and lateral control are entrusted to the automation, but the lane change maneuver is still started by the driver. Other influential hypotheses are:

- only the following vehicle accelerates in order to meet the leader one or the platoon, when the leading vehicle slows down, in fact, negative effects on the traffic flow arise;
- truck platoon members can create gaps for other vehicles to let them merge, this function can be turned on or off.

In order to ease the platooning impacts at on-ramp areas, the author identified two approaches: the creation of gaps in the platoon to allow vehicles to merge and the lane changing strategy. If the platoon is allowed to change lane before on-ramp areas, it would free the lane for the entering vehicles indeed. In order to evaluate the lane changing strategy, a Lane-change Model with Relaxation and Synchronization is considered. This model “(…) takes away some of these shortcomings by introducing a new decision structure and interaction with car-following in the form of relaxation and synchronization. Relaxation is the phenomenon of slowly decelerating upon completing a lane change in order to increase the gap to the desired gap. Synchronization is the phenomenon that a vehicle adapts its speed tot the speed of the vehicles in the target lane when about to execute a lane change maneuver. At the same time, the LMRS incorporates only seven parameters, making it relatively easy to calibrate.”

Another important conclusion drawn from the author, based on his literature review, is that human tend to accept smaller gaps when merging in a platoon if the number of trucks in formation is high: this accepted gap can be as low as 0,3 s depending on the urgency of the merging maneuver.

The simulations were conducted varying the following parameters: the number of vehicles in the platoon (2 ÷ 3) and the headway value (0,3 s, 0,5 s, 0,7 s, 0,9 s). Also, different levels of congestion were considered. The baseline scenario (without lane changing or wider gaps) resulted, from simulations, in a significant impact of Truck Platooning on the on-ramp areas; the entering point in the main branch results shifted towards the end of the acceleration lane and a significant number of vehicles is unable to merge before the end of the acceleration lane. A hypothesis that surely affected the results is that vehicles not able to merge were simply deleted, while, in reality, they still need to merge starting from a null speed, situation that could imply high collision risk. Another risk of this assumption, highlighted by the author, is that these vehicles could keep on driving on the shoulder lane and enter the main branch as soon as they find a gap.

From the yielding solution (in which the platoon adapts its gaps to allow entering vehicles to merge) an interesting output is that an increased number of merging vehicles entails major disruptions of the traffic flow on the right lane. Besides, from the simulation results, the yielding strategies seems to solve the merging problem at on-ramp areas. The lane change approach seems to reduce merging problems only for congested scenarios, instead, this happens because in free flow condition the speed difference between left and right lane is too large for the truck platoon to change lane safely. Still, in both scenarios there is an issue related to the take-over time. Being the longitudinal and lateral control automated, the drivers have the role of supervisors but don't need to continuously pay attention to the system, this could involve high take-over times, hardly compatible with the yielding or lane change strategies.

Therefore, the author identifies a role for the infrastructure that, by the means of I2V communication, could provide the platoon with the information about on-ramp locations that could allow the control algorithm to adapt the gap or change lane before reaching the on-ramp area.

2.7 Truck Platooning – Risk assessment & Safety

"In terms of safety effects, it is widely recognized in research literature that platooning is likely to lead to significantly reduced accident rates, at least for equipped drivers, which would provide an immediate societal benefit" [105]. Nevertheless, some consideration should be done in order to account for technology and operational-related risks mainly bound to the system robustness.

In a truck platoon the intravehicular distances are reduced of the space travelled by the vehicle during the driver reaction time (in which the need to brake is detected and the brake pedal is pressed). This can be achieved without compromise safety thanks to the CACC and the Dedicated Short-Range Communication that transmit the brake signal as soon as the preceding vehicle decelerates. Nonetheless, the Truck Platooning system is bound to suffer from system failure and communication delays, besides the truck platoon drives among other road users so its prone to be subjected to imposed sudden braking and interferences. Moreover, it should be noted how a greater number of heavy vehicles involves an increased magnitude, so the risk bound to the system should be lower than the one considered for the single truck.

The first main consideration concerns in-platoon collisions and is summarized in [105]:

> "In the event of the lead vehicle having to apply emergency braking, the following vehicles will automatically apply their own brakes to avoid colliding with the rear end of the vehicle immediately in front of them. Therefore, the basic capabilities of the vehicles' braking systems should also be considered and will be important under such conditions. Differences in tyres, loads, brake temperatures, air pressures, system architectures, etc. will all mean that the vehicles in a convoy/platoon will all have slightly different emergency braking capabilities. […] Therefore, a more appropriate mitigating measure may be to increase the distance between following vehicles based on calculations that allow for likely variations in braking performance. Another option may be to set each vehicle to have the same braking deceleration, based on that of the worst performing vehicle in the convoy/platoon – this, however, may have liability implications if, for example, the ultimate braking capability of the lead vehicle has been compromised to avoid in-convoy/platoon collisions, but such that it could not avoid its own collision with a non-convoy vehicle in front of it. An alternative approach would be to use similar (or ideally identical) type of vehicles in any trial. This is the preferential option and is considered likely should a large operator be involved in any trial. "

Generally, when the automation levels are low enough to keep the driver in the driving loop, the driver himself is the backup in case of system failure. However, for truck platooning the longitudinal control is fully automated so, while the driver still retains the lateral control and is, therefore, in the driving loop, the time to respond to a CACC system failure is too short for human perception and the driver can't be considered a safe fallback solution. This is especially true for strongly reduced headways, it should be defined what is the threshold under which the driver can no longer be considered responsible for the longitudinal truck behavior. More studies on the control transition should be made to assess what are the reaction times for a trained driver and how they change in a situation where the driver's foot is already on the brake pedal. As long as rear-end collisions between platooned trucks is concerned, a relevant work is [115]. In this technical report is stated how the brick wall safety criterion approach (in which the following vehicles must avoid a collision with the leading one even if this truck's speed goes suddenly to zero) is not generally applied to truck platooning. The hard-braking safety criterion is acknowledged as the most applicable, instead, in which "a following vehicle does not collide with the vehicle ahead, when that vehicle applies maximum braking until it comes to a stop". In fact, thanks to the CACC, if the braking action of the leading vehicle was applied in the same instant as in the following vehicles, the time gap would remain the same. As stated in [115], this scenario is hardly realizable due to transmission delays but, as long as these delays remain low, a residual gap should endure (in this technical report with the hypothesis of negligible transmission delays, the braking in the following vehicles is expected to start within 20 ms).

Bijlsma T., Hendriks T., A fail-operational truck platooning architecture 2017

To face this issue, in [99], a fail-operational truck platooning architecture is designed considering a headway equal to 0,5 s or lower. Lateral control is entrusted to the Lane Keep Assist, falling above the L2 automation level (SAE classification), which means that a distributed fallback strategy for failure was defined. The system considered is the one demonstrated by the EcoTwin consortium that tested a two trucks platoon on public roads and for which the drivers where still the fallback solution in case of failure. The vehicles employed could assume three states: engaging, platooning and disengaging.

> "The state/mode function sets the state for both controllers. Based on user input from the HMI function, the state/mode function can enable the longitudinal CACC and lateral LKA controller or decide to enable ACC in case the wireless communication performance decreases."

Thus, the communication channels were evaluated in their robustness. The utilization for each channel resulted lower than 0.5, indicating that no capacity problems exist from the Utilization point of view. From the latency analysis resulted that it is desirable to align the execution periods of the Embedded Control Units, in this work a fixed rate of 50 Hz was considered for the broadcasting of brake information, resulting in a period of 20 ms. Considering these parameters, the worst-case total latencies are equal to 153,4 ms and the best-case ones are equal to 9 ms. Another important consideration from the authors is that a separate, low latency, parallel safety function is desirable, this function should employ an event-driven execution and communication instead of a periodic one. To increase system reliability, the Embedded Control Units and camera sensors should be placed in parallel. The reliability of a certain number of Embedded Control Units or sensors placed in series is obtained by multiplying their individual reliability while for the parallel solution, the reliability is obtained as $R_p(t) = 1 - \prod_{i=1}^{n}(1 - R_i(t))$.

Lastly, the safety for a two-truck platooning system was assessed by the means of an Hazard and Risk Analysis that identified risks and potential hazards regarding the steering, braking and acceleration maneuver. The functional safety of the system was analyzed complying to the ISO-26262 standard. Once defined these safety-related aspects, the authors designed a system architecture able to support also automation levels 3 and 4. The required features considered by the authors are:

- heterogeneous duplex pattern architecture for L2: each truck has two channels with platooning functionality, running on different platforms. The outputs of both platforms are compared and validated only if they are close enough;
- two out of three patterns for L3 and L4: with the duplex pattern described above fail-safety is achieved but the fail back on the automation is not granted. To allow the system to fail back on the automation, in fact, three different platforms should be considered, to allow the system to continue operation in case of a single failure in one of the channels. This is a costly solution, though;
- safety executive pattern for L3 and L4: two separated channels are accounted for, with an executive which monitors the health of both the channels and decides which output should be forwarded.

E. Van Nunen, F. Esposto, A. K. Saberi And J. P. Paardekooper, 2017. Evaluation of safety indicators for truck platooning

[23] is a relevant work in which safety indicators for Truck Platooning are identified and evaluated in their capability to determine the correct moment for the beginning of a Collision Avoidance brake action. These indicators are the intended acceleration of the preceding truck, the Brake Threat Number (BTN) and Time To Collision (TTC): the former requires V2V communication while the other two indicators rely on on-board signals and sensors; “The Brake Threat Number is based on the required intended acceleration (…) to avoid a collision, assuming the worst-case braking action on the preceding vehicle.” The TTC is based, instead, on a constant velocity assumption and is obtained as the ratio between the initial distance and the speed difference between the two vehicles.

The data used to define the number of false positives refer to an 8 hours on-road experience in Belgium and the Netherlands, with a 0,5 s headway, in mixed traffic. Further, the indicators were also evaluated for 5 emergency brake tests. The total failure rate of the system is defined as the sum of false positives (starting the emergency brake when not needed) and false negatives (not starting the emergency brake when needed) per kilometer and should be lower than $4 \cdot 10^{-7}$/km in order to be comply with the Automotive Safety Integrity Level B as defined by the ISO 26262 (the same classification was adopted in [99], the ISO 26262 is applied also by relevant stakeholders such as Peloton [121]).

To evaluate a collision avoidance system that applies full braking upon activation, a safe state in which the CACC can safely take over again was defined by the authors as follows:

$$d_{r,i}(t) = r_i + h_i v_i(t)$$
$$d_i = p_{i-1}(t) - p_i(t) - L_{i-1}$$
$$e_i(t) = d_i(t) - d_{r,i}(t)$$

Where $p_i(t)$ is the position of the center of the front bumper of the vehicle i, r is a constant standstill distance and h the desired time gap. L represents the vehicle length and $e_i(t)$ is the control error. To minimize the control error, a feedforward and feedback controller are assumed, for the truck i to be able to determine the intended accelerations. Besides, a PD controller is planned to be active to estimate the control errors based on on-board radars, wheel encoders and an accelerometer. Lastly, a collision avoidance controller is added in parallel to ensure a positive distance between the two platooning trucks. Then, the safe state can be defined as e_i > 0, $\dot{e}_i$ > 0 and $\ddot{d}$ > 0.
From the emergency braking tests carried out by the authors, the threshold values identified to avoid collision (with a spacing policy defined by r = 4,4 m and h = 0,3 s) are:

- intended acceleration of the preceding truck u_{i-1} ≤ -4 m/s2
- BTN ≥ 0,93
- TTC ≤ 12,4 s

From the on-road experience data were collected regarding the scenarios in which the driver did not feel the need to take over, in order to define threshold values. The intended accelerations fluctuate between -2,5 m/s^2 and 2,5 m/s^2 and no false positive were recorded for a value of - 4m/s^2. Both BTN and TTC aren't capable to distinguish between threatening and safe situation, though, both involving a high number of false positives during the on-road experience.

Xu L., Impact of Communication Erasure Channels on the Safety of Highway vehicle platoons
As mentioned above, tunnels are critical points along the route where the potential impacts of Truck Platooning are mostly negative ones, tied to the risk assessment and to communication delays. About the latter, an important paper is [98] where the impact of packet losses is studied and different information structures that utilize radar distance sensors and wireless communication channels are compared, then some intrinsic relationships between communication resources and control performance are characterized. The paper focuses on platoons of generic vehicles, not truck platooning and on longitudinal movements within a straight-line lane, the sensor information is limited to distances while a communication channel from the preceding vehicle to the one behind transmits information about distance, speed and pedal action (braking). The safety critical condition is the one in which the distance between the vehicles is the same as the one needed to stop when the leading vehicle brakes. The safety assessment concerns erasure channels in wireless communications where the loss of a packet may be caused by erasure of one or multiple bits within the packet during transmission. Due to channel uncertainties the receiver can either acknowledge the data received or indicate a packet erasure and declare the data to be lost. The latter event is random and the channel is disconnected until another packet is received, to account for that situation, the author

models the transmission channel as a link with a certain probability to be disconnected. The objective is to understand what the erasure probability's is lower bound for a required safety level.

> "The bit erasure probability ε depends on communication resources such as power and bandwidths, as well as transmission media. In a mobile system such as highway vehicles, vehicle-to-vehicle (V2V) communication links are affected by intervehicle distances, weather conditions, obstacles, interference, and signal fading. Consequently, a detailed and accurate description of bit erasure probability for a practical system is ad hoc and extremely difficult. On the other hand, the principles and generic function forms of bit erasure probability can be established and used as a guideline in design considerations."

Inside a tunnel this probability could easily be higher than the average and should be known for the platoon algorithm to decide that is safe to hold the formation and keep the headway wide enough to face communication delays. Numerical results presented in the paper show how the minimum distance between two vehicles after the preceding one brakes change as function of the communication delays.

Even before the European Truck Platooning Challenge there were worries about the robustness of the systems in tunnels but, in the end, tunnels on the route were too short to make system failures likely, still Belgium required truck platoon to decouple 200 meters before the start of the tunnel [24]. As mentioned above, in [50] the Daimler Truck Platooning Challenge experience was described but tunnel communication failures weren't considered and a transmission delay of 0,1 s was assumed, this to assume the worst-case scenario considering that 0,1 s it's the faster rate at which messages should be sent according to ETSI and SAE.

In [102] an actuator delay is considered, caused by the actuators, the engine control unit and the electronic braking system, the total value is equal to approximately 150 ms to 500 ms and should be considered together with the communication delay (equal to 0,2 in this work) to assess the negative impact on string stability.

V. Vukadinovic, K. Bakowski, P. Marsch, I.D. Garcia, H. Xu, M. Sybis, P. Sroka, K. Wesolowski, D. Lister, I. Thibault, "3GPP C-V2X and IEEE 802.11p for Vehicle-to-Vehicle communications in highway platooning scenarios" 2018

[118] is a relevant work that aims to assess the performances of two V2V communications, in relationship with both the CACC communications and the Truck Platooning system. The two communication families considered are the IEEE 802.11p and the 3GPP Cellular-V2X (which is a close relative of the G5 hybrid solution mentioned in the previous paragraphs). The 3GPP Cellular-V2X follows the Release 14 of the LTE standard and includes an air interface called sidelink/PC5 used for direct communication between vehicles. Moreover, these V2V communications include two

modes: Mode-3 and Mode-4, the former of which needs the support of a cellular infrastructure while the latter doesn't require a cellular infrastructure and can operate also where the cellular coverage is scarce or absent). The performances of the V2V communications are evaluated by the authors through simulations based on the following performance metrics: minimum feasible inter-truck distance (considering only the performance of the wireless communications), the CAM message latency and the CAM reception probability. The performances of the communications are assessed also considering different congestion scenarios of the radio channel arising with different level of highway traffic density. A first, relevant hypothesis made from the authors concerns the market penetration of cooperative vehicles able to broadcast CAM messages and contend the same radio channel exploited by the platoon to maintain a safe communication between trucks. In fact, in the simulations, every vehicle on the highway is considered able to send and receive V2X messages. Moreover, it is worth reporting the algorithm of the CACC controller evaluated by the authors for different V2V communications:

$$\ddot{x}_{des,i} = \alpha_1(d_d - d_r) + \alpha_2(\dot{x}_i - \dot{x}_{i-1}) + \alpha_3(\dot{x}_i - \dot{x}_1) + \alpha_4\ddot{x}_{des,i-1} + \alpha_5\ddot{x}_{des,1}$$

Where i = 1 is the leading vehicle and every i > 1 is a following vehicle, d_d is the desired constant headway value, d_r is the distance from the preceding vehicle (derived through on-board sensors), $\dot{x}$ is the speed value and $\dot{x}_i - \dot{x}_{i-1}$ is the relative speed measured by the radar. $\dot{x}_1$ is the speed of the leading vehicle broadcasted through V2V communications and $\ddot{x}_{des,i-1}$ is the desired acceleration of the preceding vehicle (the desired acceleration of the leading vehicle is broadcasted through V2V). α are weight factors. It is relevant to note that this kind of control law allows the leading vehicle to broadcast its desired acceleration and not the current value, this way the broadcasted value is the acceleration that is presumably going to become effective after the actuation lag. The authors called this solution a "predictive CACC" that allows to overcome the time (and therefore the intra-vehicular distance) resulting from the actuation performed by the lower controls. This way the biggest time interval after the human reaction times is overcome and the distance between trucks can become even smaller. It should be highlighted that the works uses as performance metric the minimum headway achievable through V2V connections, without considering other limiting factors such as reduced adhesion or the drivers psychological state, the need to overcome the actuation lag, in fact, doesn't seem as relevant as in this case when time gaps are higher than 0,5 s (the actuation lag of trucks is assumed equal to 20 ms in this work).

Thus, the authors proceed with the analysis mentioning one of the biggest limits of the IEEE 802.11p communication which lies in the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) that, in congested scenarios, suffers from higher latencies and an increased probability of data packet collision. These limits result in a lower CAMs transmission rate.

The simulations carried out considered a platoon composed of ten trucks, preceded by a jammer which drives with well-defined acceleration/deceleration cycles, the leading vehicle is equipped with the ACC and adapts its driving to the jammer's one. The traffic density on the three remaining lanes during the simulations is set equal to 0,5,10, 20 cars/km/lane and every vehicle broadcast 300-byte CAMs every 100 ms.

For each scenario, the average inter-truck spacing is the performance metric related to the headway for which no more than one crash in 100 simulation runs is obtained which means a crash-rate ≤ 1%, this residual percentage can be considered preventable through emergency braking, for example (the authors considered this assumption to be conservative enough). The other two metrics are the CAM message latency and the CAM perception rate (which is the percentage of CAMs transmitted successfully transmitted and received). Therefore, these scenarios were simulated through the Nokia's internal 3GPP system simulator to evaluate 3GPP Cellular-V2X communications and through a simulator developed by Poznan University of Technology to evaluate the IEEE 802.11p communications. Starting from a very low value of 0.2 m, the distance between trucks was incremented of 0,2 m until the performance of 1 crash every 100 runs was obtained, thus obtaining the minimum CACC feasible headway for different communication technologies and different levels of traffic density.

The results obtained by the authors are summarized below:

- with the IEEE 802.11p, the average feasible headway (measured from the back bumper of one truck to the front bumper of the following one) increases from 1 to 11 m when the traffic density increases from 0 to 20 cars/km/lane;
- with 3GPP Cellular-V2X communications Mode-4 the same spacing increases from 1,6 to 2,4 m (again it should be highlighted that this feasibility considers only the connection's requirements);
- with 3GPP Cellular-V2X communications Mode-3 the same spacing doesn't change with traffic density and is equal to 0,8 m.

When considering only the average CAM latency, the IEEE 802.11p communication sees this value increasing but never surpassing 1 ms, this value is higher for both Mode-3 and Mode-4 (respectively 7 and 10 ms on average). From the results appears that CAM latency doesn't impact the CACC performance (and, therefore, the feasible headway) in a relevant way, though. In fact, as reported above, the IEEE 802.11p is the one that reaches the higher minimum headway value (that ranges between 1 and 11 m). This phenomenon arises, in fact, because the inter-truck distance is strongly affected by CAM reliability rather than CAM latency. With IEEE 802.11p connection the reception rate of CAMs decreases as the traffic density increases because the number of collisions of data packets increases as well due to the CSMA/CA limits. The reception rate of the last truck in the platoon from the leading one can drop below 85% for 20 cars/km/lane as results from the simulations carried out by the authors. Another relevant result of these simulations is that the packet loss between the following truck and the preceding one doesn't decrease relevantly with 802.11p communications (it decreases to around 97% for a traffic density of 20 cars/km/lane). Thus, multi-hop solutions don't seem to be really affected by the number of cooperative vehicles on the surroundings. Moreover, the authors mentioned how for platoons composed by a maximum of five trucks the improvement of a Cellular-V2X Mode-4 communications is marginal when compared to an IEEE 802.11p communication and is, thus, relevant only in long-term scenarios. Besides, communications between the following trucks and the leading one weren't considered in this paper and should be evaluated in future works (in order to evaluate also solutions as the one presented in [32] that allow to consider multi-brand platooning). Lastly, in the conclusions, 5G solutions are explicitly mentioned as future V2X applications.

D. Bevly, C. Murray, A. Lim, R. Turochy, R. Sesek, S. Smith, L. Humphreys, G. Apperson, J. Woodruff, S. Gao, R. Bishop, D. Murray, A. Korn, J. Switkes, S. Boyd, B. Kahn, "Heavy Truck Cooperative Adaptive Cruise Control: Evaluation,Testing, and Stakeholder Engagement for Near Term Deployment: Phase Two Final Report", FHWA Task Report, April 2017.

[122] faces also another important challenge for the Truck Platooning system: the assessment of the DSRC system's performance. In fact, during the field tests carried out by Auburn University together with Peloton Technology, the DSRC system employed was evaluated and an algorithm aimed at tackling the channel congestion issue was designed and optimized on the basis of the field tests' results. In the end, an adaptive ICTL algorithm able to achieve a reduced bandwidth consumption was designed and tested. It should be highlighted how channel congestion is not going to be a relevant problem in the short term, when few platoons and cooperative vehicles will travel European public roads, but will became a pressing subject as soon as certain levels of market penetration of these technologies are reached. Having a congested channel means an increased rate of packet losses and higher risks of transmission delays and safety critical scenarios such as the ones analyzed in the previous paragraphs.

The metrics that were examined during the field tests are:

- the wireless channel used for DSRC;
- data rate, which specifies how many bits of data can be encoded per second. It represents the capability of the Media Access Control layer and of the Physical layer;
- message rate and message size;

- pairwise delivery ratio which represents the ratio of messages delivered from either one of the two antenna referred to the total pairs of messages sent. This metric is applicable with the alternate antenna configuration in which the message is transmitted by both antennas and if any of the two messages is received correctly the delivery of the message is considered successful;
- which one of the two antennas should be used, as a function of the road topology and of the platoon position on the road.

Different configurations were tested, for example one of the scenarios was “Large separation distance in an open area without trailers”. In this scenario, the distance between the two antennas was equal to around 80 m. The output from the analysis of scenarios such as the “Large separation distance in an open area without trailers” concerns, for example, the antenna that should be used to enhance the delivery ratio (in the above scenario the packet delivery ratio resulted close to 100% even for high data rates). Other tested scenarios were: “Close distance with building on one side without trailers”, “Large separation distance uphill and downhill” and “Large separation distance with lead truck turning”. For each one of these scenarios the delivery ratio was measured and commented for each one of the two antennas, moreover, considerations about the reflection of the signals with external objects are made. It should also be noted that with the alternate antenna configuration the issues noticed through curves (in which the message of the external antenna can be hindered). Generally speaking, the authors concluded that the inside antenna performs better through curves while the outside one performs better on straight lines.

> “One of the important findings from the performance tests was that, by utilizing both antennas alternately and using lower data rates, DSRC communication is generally very reliable and can support platooning applications very well”

Moreover, an extreme case study in which the channel congestion could arise is presented and used to design an efficient algorithm but is not reported in this Ex-Ante, please refer to the authors’ work for the complete dissertation. The results achieved by the tests on the adaptive ICTL algorithm show that the bandwidth consumption can be reduced by over 50% and therefore postpone the point when the congestion control strategies are activated and the DSRC must be limited in a fashion similar to the coexistence strategies. The activation of congestion control strategies, in fact, limits the possibilities granted by DSRC and, thus, the reliability of the service, as stated by the authors. A last, important consideration presented in [122] should be reported:

> “(…) regarding channel congestion regarding near-term commercial DATP systems, the operational parameters of platooning can be adjusted to respond to many conditions, such as weather and traffic density. Any performance degradation in the communications

channel, due to congestion and other factors, could be detected by a platooning system before it reaches a critical stage so that the inter-vehicle gap could be widened or the platoon dissolved until conditions improve. Decisions to approve a new platoon or dissolve an existing platoon are made at a much lower frequency than is required by BSMs [Basic Safety Messages]. Unlike active safety systems relying on V2X, platooning systems are not required to be "always on" and thus can be expected to adapt to degradation of the channel".

2.8 Most likely implementation scenarios and related impacts

Truck Platooning has still to become reality on public roads, this means that no legal framework exists and that, before evaluating the impacts on traffic efficiency, environment, safety and user acceptance, the most likely level of automation, features, inputs and coordination schemes for Truck Platooning must be defined. At the state of the art is not realistic to consider a reserved lane that is not dynamically allocated or platoons longer than 2 or 3 vehicles (in the short term). In [102] is stated that, from a technological point of view, the only limitation in platoon sizes would be the communication range of DSRC (approximately equal to 300 m) if all the following vehicles require information from the leader vehicle. When the CACC algorithm employs only information from the immediate predecessor, then the length limit could be nearly infinite[6]. Actually, more than 3 trucks in a platoon could result unable to perform lane change maneuver or be an intolerable obstacle for other road users at ramp areas, causing safety critical scenario but also creating a negative image for the public opinion. This aspect should not be neglected: public opinion is, in the end, what causes or hinders the support by political stakeholder, a support that proves to be fundamental in the short term when the technology is still in the deployment phase and the legislations across Europe must be updated. According to Richard Bishop, from Peloton, the first generation of platoons in the USA will be two trucks only, due to the possible problems at short on- and off-ramps [7]. During the European Truck Platooning Challenge both two trucks and three trucks platoons have been deployed on public roads [24] while, within the activity of C-Roads Italy, IVECO as a partner is planning to deploy three trucks platoons in order to assess impacts during field tests.

[6] Shladover, S. E., C. Nowakowski, X. Y. Lu and R. Ferlis (2015). Cooperative adaptive cruise control: Definitions and operating concepts. Transportation Research Record. 2489: 145-152

Figure 3 - IVECO trucks - European Truck Platooning Challenge

As previous mentioned, the headway value granted by the CACC can be as low as 0,5 s that, while driving at 80 km/h, means a distance of 11 meters. While the speed value is consistent through the bibliographical review (the leading vehicle should drive at maximum 85 km/h, the following ones cannot exceed 90 km/h), the same can't be said about the time gap. A lower time gap means greater fuel savings but also lower TTC during cut-ins, greater communication delays impacts and longer disaggregation times. In order to choose the optimal value, the following factors should be considered:

- the time gap between heavy vehicles without CACC ranges from 1,2 to 1,5 s, so a headway greater than 1 s could nullify Truck Platooning benefits and make the business case less attractive;
- the human driver must be still considered, while assuming that in the short term only properly trained driver will be in charge of maintaining a platoon it should be also noted that gaps lower than 16,9 m usually intimidate less-experienced drivers and gaps lower than 7,5 m make them feel unsafe [39];

- in some of the European countries a headway of 0,8 s is not sufficient to prevent cut-ins. “A following distance of 0,8 s and above meant more frequent merging in traffic and overtaking manoeuvres.” [100];
- the number of vehicles in the platoon, together with the headway kept, determines the time needed for the platoon to dissolve. Both parameters should be chosen accordingly;
- a dynamic headway should be considered and implemented in the algorithm of each vehicle, especially when the mono-brand solution is chosen.

Therefore, the headway value cannot be a univocal one but should be chosen according to the number of vehicles in the platoon, the planned route, the number of ramps and their proximity to each other, the longest tunnel on the road and the regional cut-in inclination. In bibliography the most consolidated values range from 0,5 to 1 s. In Italy Iveco plans to deploy platoons with a headway of 0,8 s.

These values affect fuel savings so, clearly, in an Ex-Ante phase only a range of expected value can be given. From the bibliographic review a more defined percentage was derived compared to the 5-20% [36] which account for the maximum and the minimum value achievable. The majority of studies assumed an air drag reduction equal to 10%, an average among the drops for each vehicle in the platoon, as seen before, this value changes with the headway, the number of trucks, environmental conditions and type of coolant, though. Besides, it must be considered that the fuel savings vary also based on the truck position across the platoon, the leading vehicle doesn’t enjoy for the same benefits as the following ones. As the number of following vehicles increases, their aerodynamic benefits grow before settling on an asymptotical value [72]. In [105] both SARTRE project[7] and Energy ITS project[8] are mentioned, in the former fuel savings reached 8% for the leading vehicle and 16% for the following ones, in the latter those values were equal to 9% for the first truck and 22% for the second truck.

In literature there is still no headway value under which aerodynamic benefits decrease or settle. Moreover, to assess fuel savings and environmental benefits, different field tests across different European countries must be performed. Also, these field tests should be designed to consider for

[7] Eric Chan, “Cooperative control of SARTRE automated platoon vehicles”, October 2012, ITS World Congress

[8] Sadayuki Tsugawa, “Final report on automated truck platoon within Energy ITS project”, October 2013, International Task Force on Vehicle Highway Automation

the numerous parameters that can affect the Truck Platooning impact under different implementation scenarios.

> "In order to collect statistically significant data for an impact assessment, the effect of variations encountered during daily haulage operations must be accounted for. These variations could include load, weather, seasons, driver and routes, and these are known to have significant effects on, for example, fuel economy. Achieving statistically meaningful results in light of these variations will be an important factor in determining the overall size of the trial in terms of the number of trucks vehicles/drivers and the overall duration of the trial." [105]

This way, a reliable and complete set of inputs could be obtained and used for following modelling works, evaluations and the design of an adequate business case. Field tests are a subject still dependent on national legislations. A benefit distribution among the vehicles forming a platoon is needed for the leading vehicles to not be penalized, the issue can be solved by the means of mono-brand platooning or of a Platooning Service Provider. In the former approach the same company purchases the fuel for each vehicle, so the savings can be summed together; a service provider instead should share these benefits among all the participants: how that should happen is not yet defined due to the lack of a detailed business case. Besides the service provider solution is probably not relevant in the short term, but an intermediate approach is proposed in [33], where the fleet coordination and the platoons' formation is entrusted to a set of controllers on the main intersections. Then, by the means of the controllers, each truck receives the speed that must be held to reach the intersection at the same time as the other vehicles with which to form a platoon. This way there is no need for an external provider, moreover this type of solution allows to solve the problem of finding data, as for now, in fact, the position of trucks on the road isn't registered in a common database but is only available for the truck company. A platoon service provider should be able to access to all these data in order to function properly, while the controllers should just apply an algorithm that accounts for the vehicles in the broadcast range. Also, the approach presented in [33] bypasses the issue that all the optimization models must face, the solution of an NP-hard problem, it only needs a well-tuned algorithm and V2I communications to allow the vehicle to send the controller its position, speed and destination. The controllers' approach has not been extensively examined in literature, it is still necessary to assess how much fuel can be saved (simulations returned savings by 2% with a fleet of 300 trucks and by 9% with a fleet of 7.000 trucks) and to what extend to channel more heavy vehicles to an intersection can impact on the whole traffic flow. In the conclusions, in fact, the authors expressed the need to validate the results with field test and to consider, in future works, the influence of the traffic conditions on the formation of the platoons coordinated by controllers (and then quantify the influence on fuel savings). Other simulations should be carried out on other road networks:

especially for the controllers' approach the infrastructural features have a great influence, therefore it is necessary for this type of studies to be conducted across all European countries, at least along the main freight dedicated corridors.
Besides, while defining the Truck Platooning implementation scenario in the short term, the level of automation should be considered. Surely in the short term the longitudinal control will be granted to the CACC for all the following vehicles, along most of the route, the driver will be in the driving loop all the time, hands on the steering wheel and eyes on the road. Longitudinal control will be resumed only while dissolving or leaving the platoon. This platoon system can be considered in the L1 of the SAE classification [61].

> "Automation at this level involves one or more specific control functions; if multiple functions are automated, they operate independently from each other. The driver has overall control, and is solely responsible for safe operation, but can choose to cede limited authority over a primary control (as in adaptive cruise control), the vehicle can automatically assume limited authority over a primary control (as in electronic stability control), or the automated system can provide added control to aid the driver in certain normal driving or crash-imminent situations (e.g., dynamic brake support in emergencies). (…) As a result, there is no combination of vehicle control systems working in unison that enables the driver to be disengaged from physically operating the vehicle by having his or her hands off the steering wheel AND feet off the pedals at the same time".

Technology is already capable of granting higher automation level [35, 84], but the automation level will stop at L1 because the legal framework is not ready for higher levels and the system still has to be validated on public roads. For L2 Truck Platooning, for example, the lane keeping assist can assume the lateral control, leaving to the driver just the role of supervisor, also, sensors can be employed to keep the truck aligned with the one ahead, giving a redundant fallback system for when the lane markings are lacking or ruined.

> "This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. Vehicles at this level of automation can utilize shared authority when the driver cedes active primary control in certain limited driving situations. The driver is still responsible for monitoring the roadway and safe operation and is expected to be available for control at all times and on short notice. The system can relinquish control with no advance warning and the driver must be ready to control the vehicle safely. An example of combined functions enabling an L2 system is adaptive cruise control in combination with lane centering. The major distinction between L1 and L2 is that, at L2 in the specific operating conditions for which the system is designed,

an automated operating mode is enabled such that the driver is disengaged from physically operating the vehicle by having his or her hands off the steering wheel AND foot off pedal at the same time" [61].

Still referring to [84], some considerations can be done. In 2017 Scania launched an experimentation in concert with Toyota and the port of Singapore authority where four-trucks platoons should travel between terminals. Also, the following vehicles are intended to be automatically guided, with no driver on-board, the planned route connects different terminals and crosses public roads. Higher automation levels, in strongly freight oriented realities, can be exploited, even considering more than two or three heavy vehicles in formation. Scania's interest emphasizes how the application of truck platooning is not confined to cross-border situations (where, still, the potential benefits are undoubtedly superior) but can also find applications in goods handling and terminal management. The use of the platooning trucks for the movement of containers between terminals, in fact, does not take advantage of the aerodynamic reductions due to the lower held speeds. It is however understandable how a favorable business case can emerge if the driving of the following vehicles without a driver is permitted [35], experiments in this sense should be conducted in protected realities such as the terminal ones. Also, the following consideration can be done:

> "Trucking as we know it today is a highly labor-intensive industry. We face a shortage of truck drivers. In this regard, truck platooning technology presents us with an opportunity to boost productivity in both the port sector and the trucking industry. It will also open up opportunities for truck drivers to take on higher-skilled roles as fleet operators and managers" Mr Pang Kin Keong, Permanent Secretary for Transport and Chairman of the Committee on Autonomous Road Transport in Singapore (CARTS).

This is also true for the European reality; a higher level of automation could produce two main benefits: it could make the work as truck driver less deteriorating and more attractive to increase the workforce and it could reduce the number of drivers required (this, certainly, on a more wide time horizon, when autonomous vehicles will be able to drive on public roads). The economic benefits tied to these two aspects will not be evaluated in this Ex-Ante, being projected on an intermediate time horizon and depending strongly on the implementation scenarios and the European legal framework. In [112] a labor cost reduction is assumed to consider medium-long term scenarios in which following vehicles can travel without driver or drivers in following trucks become able to perform other activities, in this thesis a decreased labor cost makes the platooning beneficial for more than half of all the Dutch truck trips considered (for a penetration rate of 50%). It's also important to highlight how the Truck Platooning system can start with lower levels of automation and

function as first deployment test case, and then progress towards full automation, being the first transport system to involve each one of the SAE level.
Not only fuel savings are bigger for truck platoons, the fleet system as a whole can be coordinated to maximize these benefits and that is a feature that no other transportation system have. Besides, the purchase cost for technological equipment affects less a heavy vehicle than a car.

> “CV [Connected Vehicle] is more significant for heavy commercial vehicles than for light vehicles because the organized nature of heavy vehicle operations benefits more from connectivity. Fleets have an important role to play in deploying the technology, engaging with smart cities and communities, establishing connected corridors and precincts, and developing new accommodations for heavy vehicles, including signal priority and truck parking.” (Evolution of Technology for Commercial Vehicle Safety - Sweatman P. 2017)

> “The electronic equipment needed to automate a truck should not be very different from equipment needed to automate a passenger car, since its functions are essentially the same. It means that the cost of automated system for an ACT should be almost the same as a passenger car. However, a heavy truck would typically cost much higher than a passenger car. This factor makes the potential economic return from an investment in automation equipment significantly more attractive for a truck than for a passenger car.” (Design and Control of Automated Truck Traffic at Motorway Ramps. – Tabibi M. 2004)

Below two figures are showed, to summarize the main subjects to consider and parameters to choose while designing a truck platoon.

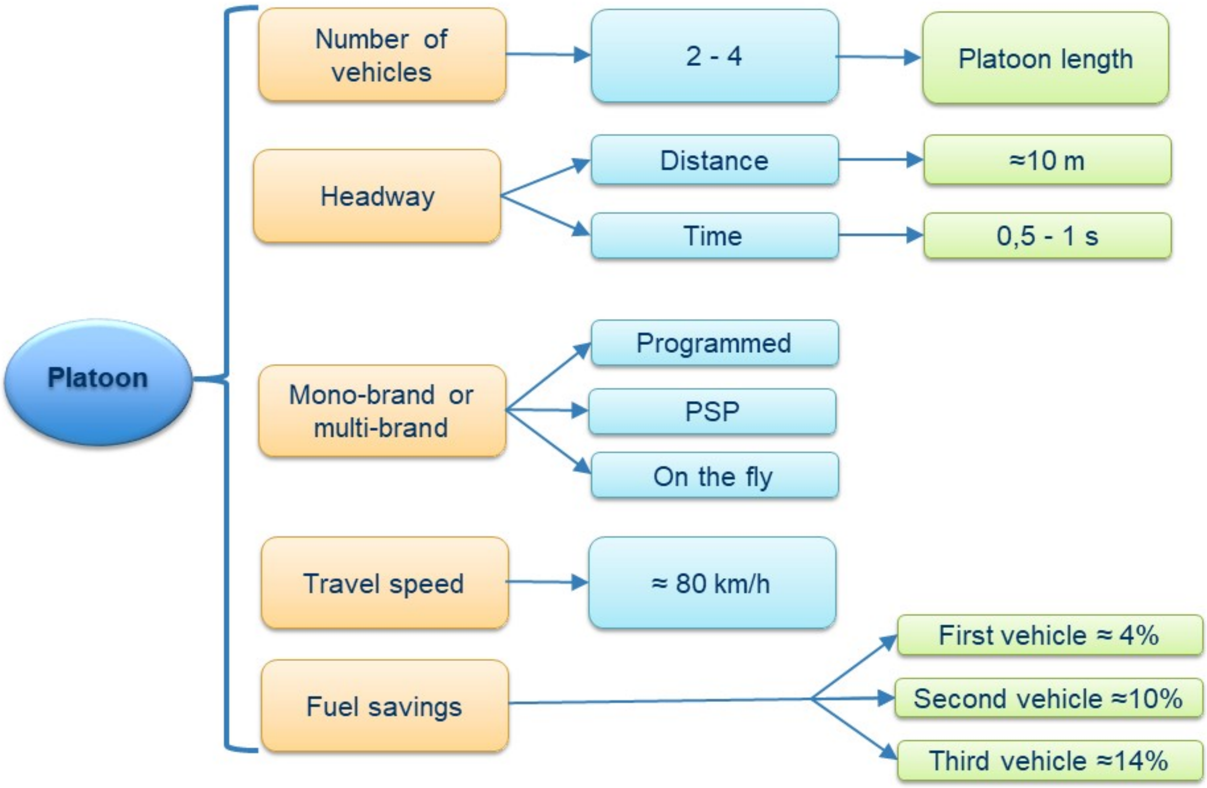

Figure 4 - Single platoon features

About the "on the fly" solution is worth highlighting the creation of the ENSEMBLE consortium, sponsored by ERTICO [101], which includes all six European commercial truck manufacturers and is led by TNO. The aim of the consortium is to implement and demonstrate multi-brand truck platooning before the end of 2021.

"The aim of the ENSEMBLE project is to ensure safe platooning when using different branded trucks and carry out impact assessment for infrastructure, road safety and traffic flow. (…) Also, the impact on fuel consumption, drivers and other road users will be established".

In 2021, a multi-brand truck platooning demonstration on public roads is planned.

Multi-brand platooning seems to be an accepted objective among the different stakeholders, together with the needed standardization of communication protocols [100], moreover, the definition of a certification system for drivers and companies seems to be a good solution to build driver acceptance, especially in the following trucks that must entrust part of the driving control to the leading vehicle driver. The "on the fly" solution can be also referred as dynamic platoon formation as in [112].

Generally speaking, every company should equip its trucks for truck platooning in an interoperable mode, in order to allow every vehicle to join every platoon, despite having to cooperate with competing companies. That should be done from the beginning, even if in the short term the only platoons will be mono-brand ones. Doing so won't preclude future scenarios in which the maximum benefits could be obtained from Truck Platooning.

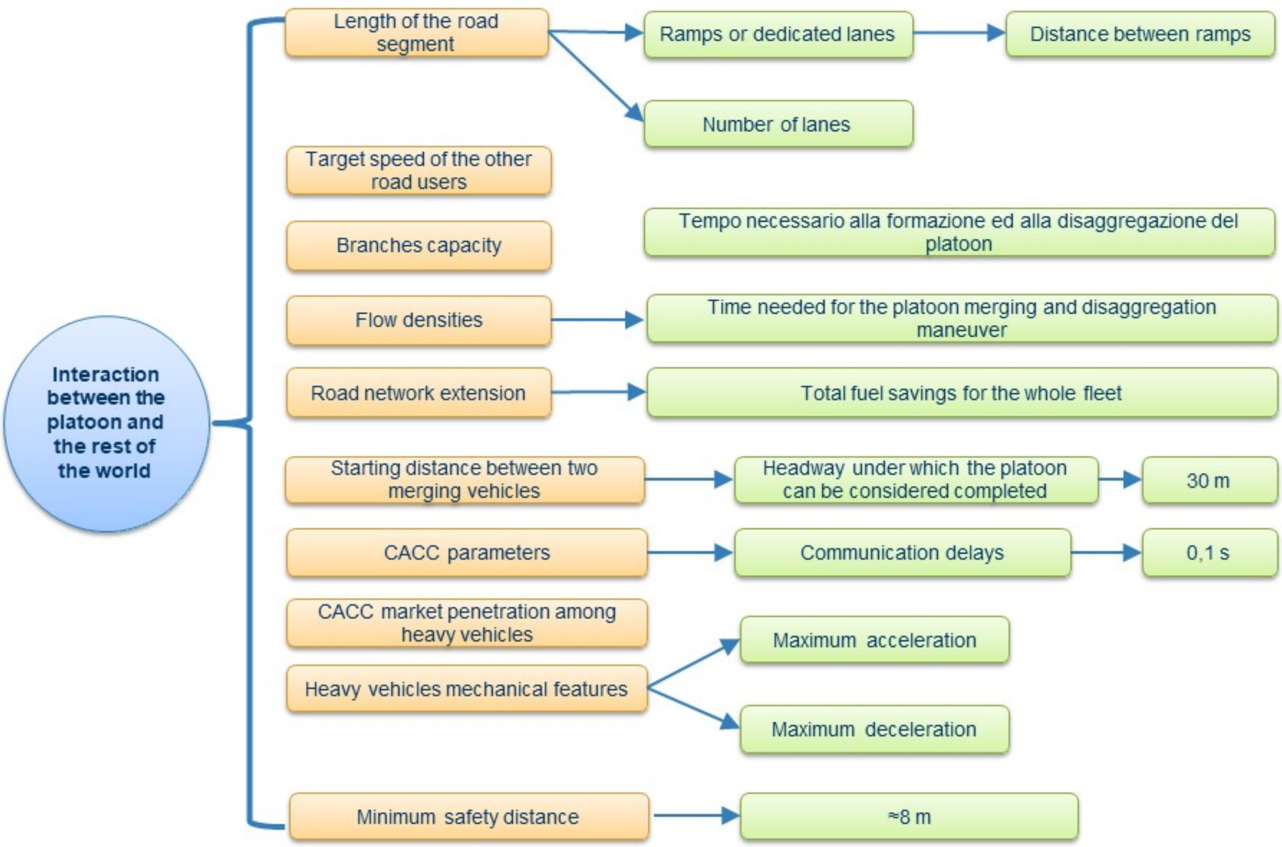

Figure 5 - Platoon and other road users' interactions

As long as the connection V2X is concerned, the implementation scenario is more defined, standards are already defined by ETSI and so are technical features and operation specifications for WIFI ETSI ITS G5. The possible variables to consider while defining and implementation scenario concern Road Side Units availability for V2I communications (for which standard ETSI are defined too), not every road branch will be equipped with RSU and the coverage on the network should be defined before the evaluations. Also, the possibility of employing hybrid communications should be investigated, if that is the case the Internet of Things standard should be assumed.

Considering what has been presented on Chapter 2, then, it is clear how Truck Platooning as a system can be implemented in the short term and lead the way to successive levels of automation on the road. In fact, the adaptation of legislative frameworks, the definition of exemption procedures, a widespread campaign of field tests across Europe and, above all, a first interaction between road users and semi-automated vehicles are all subjects that can be addressed by promoting the implementation of Truck Platooning. The pre-organized nature of the system and the likely consistency of the business case make this system independent and valid by itself. While a single CACC equipped vehicle on the road obtains no benefits from the technology, a single truck platoon travelling on the road still benefits from air drag reduction and fuel savings. Moreover, the implementation of a L1-L2 platoon does not inhibit the development of the technology towards higher levels of automation. There are already local experiences of autonomous following vehicles on which no driver is needed, besides, in the medium term, the ability to remove the driver from the driving loop and make him able to perform other tasks (or rest) can be explored. Therefore, Truck Platooning proves to be relevant and potentially a pioneer system in the autonomous driving market also in the intermediate levels before complete automation, deserving the spotlight both in the short, medium and long term.

2.8.1 Overview

To summarize the relevant bibliographical review carried out, the following table is reported:

Impacts driving from the bibliographical review		From field test and/or testbed	From modeling works	Research Effort
Presence of platoons among the traffic flow able to affect the overall traffic efficiency	> 20 %		✓	-
Fuel savings	≈ 5÷15 %	✓		++
Impact of aerodynamic devices on fuel savings	≈ 0,5 ÷ 2 %	✓		+
Number of cut-ins/100 km	≈ 3 ÷ 7	✓		-
Delays in the platoon formation compared to the free flow scenario	4 ÷ 83 %		✓	+
Impact on capacity of the platoon disaggregation before ramp areas (compared to the baseline with no disaggregation)	Up to + 15 %		✓	+
Passenger-car equivalent for a truck platoon	0,46 * PCE_{TRUCK}		✓	-
Increase of the travelable distance between rest-times	25 %			-
% of vehicles unable to enter from on-ramps	Up to 10%		✓	-
Operational parameters		**From field test and/or testbed**	**From modeling works**	**Research Effort**

Air drag coefficient	0,6	✓		++
V below which the aerodynamic benefits become less relevant	50 km/h	✓		+
Feasible time gaps	0.3 ÷ 1 s	✓	✓	++
String-stable time gap	> 0,7 s	✓		+
Minimum safe distance between trucks	≈ 8 m	✓		++
Number of trucks	2 ÷ 4	✓	✓	++
Distance needed for the disaggregation of the platoon	2 ÷ 5 km		✓	+
TTC safety critical value	1,5 s	✓	✓	++
Worst-case latencies considered to assess the robustness of the system	≈ 150 ÷ 200 ms	✓	✓	+
Transmission delay considered while testing the system	0,05 ÷ 0,1 s	✓		+
Feasible difference in braking capability between trucks	≈ 0,883	✓		+

Table 1:Summary of impacts and of operational logics

It should be noted that this table is a summary of the analysis carried out in Chapter 2, thus the ranges of values can be rather wide, being the results of different studies using different methodologies and various boundary conditions. Moreover, the strength of the results is reflected in the research effort column, in which (++) is the most consolidated value while (–) represent a result that should be investigated in a greater number of studies or that should be analyzed with different boundary conditions and in a greater variety of environments. This ranking is based both on the number of studies found on the subject but also on the reliability of the research body involved. For example, some of the results ranked (+) obtained this result on the basis of the number of research papers, reports and deliverables that faced the topic; other ones obtained the same rank when one of the sources is the work of a well-known institute or a researcher whose expertise on the subject is widely acknowledged, even if accounting for a smaller number of sources. Another consideration that should be made is that not only figures are the result of the bibliographical review: another valuable contribution is the identification of the theoretical framework that should lead to a major understanding of the Truck Platooning system and the related functional logics. A multidisciplinary approach was adopted with the aim to identify all the intertwining factors that can affect the overall functioning of the system, in order to give the tools to the future evaluators for a flexible and efficient approach towards the assessment of the Truck Platooning system.

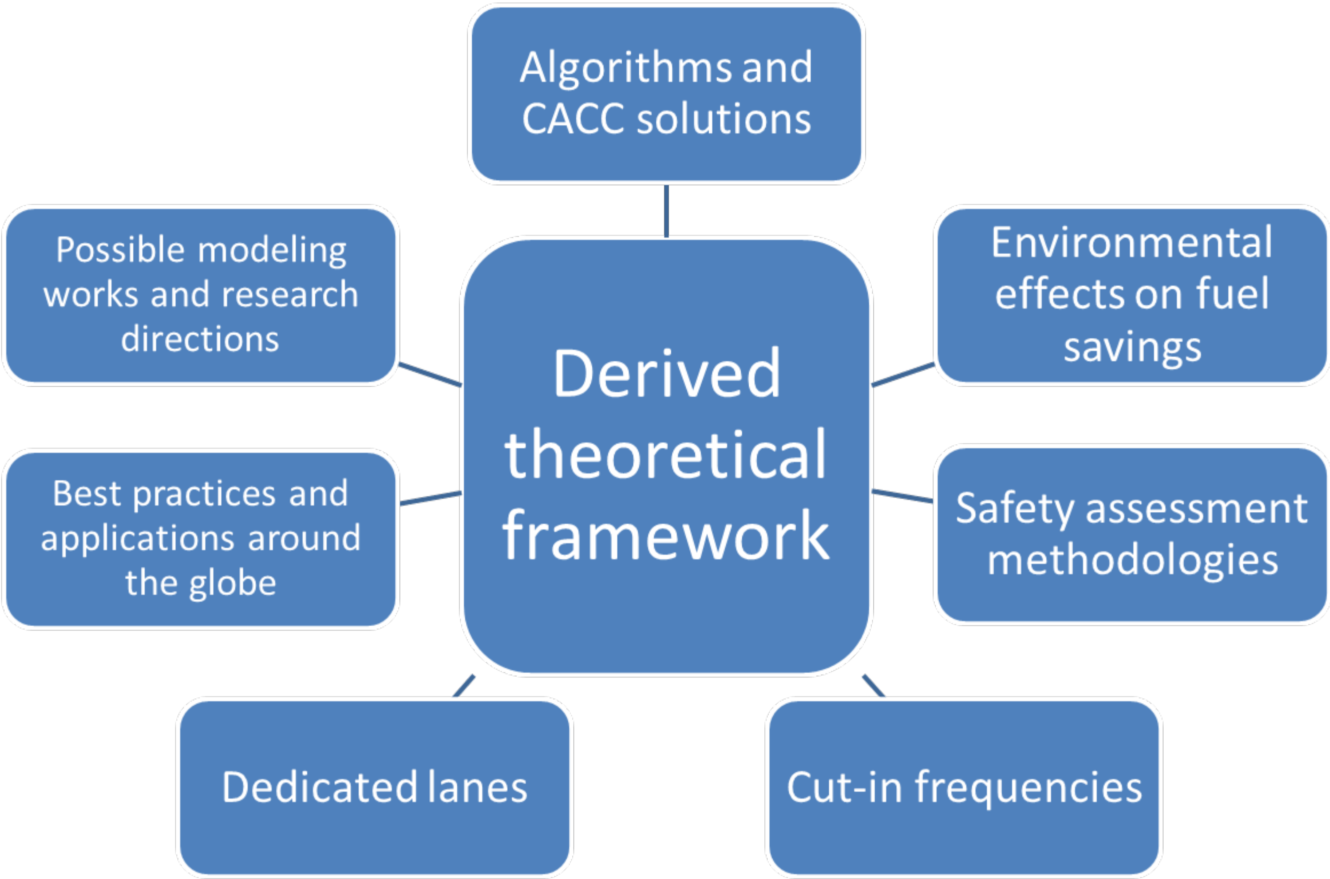

Figure 6 - Derived theoretical framework

3 Truck Platooning impact evaluation

In this chapter guidelines for the evaluation of Truck Platooning implementation impacts will be presented. The evaluation will concern the following impact areas:

- Traffic Efficiency
- Safety
- Environment
- User Acceptance

The scenarios considered will concern mono-brand truck platoons on public roads (specifically, highways), to focus on the short and middle-term impacts based on the most likely implementation defined in chapter 2 for Truck Platooning.

For each scenario the inputs and outputs required to assess the impacts will be highlighted, both for field tests and for simulation works. The followed approach is based on "Research and Sub-Research Questions" as presented in the Evaluation and Assessment Plan [129]. This methodology, applied to the Truck Platooning system, produced the following outputs for each impact area:

- Research Question: how Truck Platoon and the related maneuvers are expected to impact on traffic flow? Which are the possible changes in the behavior of other road users? What influence does the platoon have on the infrastructure (and vice versa)?
- examples of Sub Research Questions could be "How do drivers change their behavior when approaching a truck platoon?" or "How is the truck platoon affected by the surrounding traffic flow?" The changes of the parameters that characterize the traffic flow/platoon driving are investigated for each relevant maneuver; data requirements are mentioned;
- suggested methods and tools to quantify the effect of truck platooning on the impact areas listed above are mentioned, referring to the bibliographical review in chapter 2. Parameters needed as output and how to measure them will be described, suggestion about the field test designs will be offered (i.e. while designing a field test on public road, an operational domain should be defined regarding road, weather and light condition or about traffic densities and compositions).

Another methodology that strongly influenced the impact assessment carried out through this Ex-Ante is the one arising from the TEMPO programme and the Easyway guidelines (aimed at the evaluation of the implementation of ITS systems).

“Second, the evaluation before implementing (ex-ante) allows to verify if the expected results are the ones actually obtained after the implementation and guarantees a baseline useful for following evaluations (ex-post)” [128]

Moreover, as reported in [128], an evaluation should include:

- a clear definition of where and in what environment the Intelligent Transport System should be/was applied to allow an easier comparison of the results;
- a clear description of the methodology applied for the evaluation;
- a set of indicators standardized or, at least, widespread across the European countries;
- an indication about the statistical relevance of the obtained results.

The requirements listed above refer to a complete evaluation. Nevertheless, in this Ex-Ante evaluation, where possible, the same guidelines where followed to define the methodological framework.

Because Truck Platooning is not yet implemented on public roads, it is not possible to obtain complete numerical results bound to its implementation. Therefore, the main contribution of this Ex-Ante evaluation consists in the bibliographical review listing the most common results, when available, presented in chapter 2, and in these guidelines drafted to guide stakeholders in evaluating the impact of the Truck Platooning system in a specific implementation scenario. In chapter 4 guidelines for the jointed impacts of Truck Platooning and Day 1 C-ITS services will be defined.

How to investigate in depth each scenario, what data requirements to meet and output indicators to measure should be decided by the evaluator, on the basis of the test specificities and of the regional features. Moreover, it should be noted that these evaluation guidelines have been designed to be applicable in general scenarios and are not referred to specific field tests or modeling works carried out in the C-Roads Italy activities (during which some field tests will be performed, but not every subject listed in the following paragraph will be evaluated).

The last consideration that should be done is that neither Chapter 3 nor Chapter 4 are conceived as a report but rather as a tool. Namely, both these chapters should be used as tools supporting the design of field tests and modeling works. An evaluator approaching this last part of the Ex-Ante should know the objectives of his evaluation activity and should search them among the wide set of research and sub-research questions provided, rather than go through all the following pages mindlessly. Once the Use Cases and the impact areas to be evaluated are identified, the relevant information provided could be used as a basis for the design of the next assessment works, providing both a theoretical framework and the list of parameter and data requirements that should be obtained.

3.1 Traffic Efficiency

3.1.1 Research Question: How does the merging maneuver of the platoon impact on the traffic flow? How does the traffic flow impacts on the merging maneuver?

To form a platoon, two trucks must draw near each other on the same lane, this can be achieved through acceleration of the following vehicle (the leading one can decelerate or keep its driving speed stable). If the leading vehicle slows down it produces a moving bottleneck. On the other hand, increased levels of congestion involve the presence of other vehicles between the two trucks. If the traffic density and the speed difference between the lanes grow to relevant values, the time needed for these vehicles to change lane increases, together with the time necessary to the two trucks to draw close enough to form a platoon.

- *How long is the queue behind the leading vehicle?*

  A decelerating leading vehicle could cause cars and trucks to queue behind him, waiting for the time to change lane and overtake. This waiting time should change in function of traffic density on the other lane and speed difference between the one held by the leading vehicle and the one held by vehicles on the other lane.

- *How does the merging time changes as a function of the level of traffic density? For what values does the truck platoon formation result completely hindered?*

  Higher level of traffic density causes more vehicles to stay between the two trucks, beyond a certain value the delay in the platoon formation becomes intolerable and the maneuver is stopped. Besides, external vehicles between the trucks causes the following one to accelerate and decelerate more often, in order to prevent other external vehicles from cut-in and queue before itself.

Assessment instrument

The merging maneuver can be investigated both through field tests and through modeling for which some literature works can also be considered [37]. The field tests should focus on the determination of human behavioral parameters, such as the propensity of the queued vehicles to change lane.

3.1.2 Research Question: How does the disaggregation maneuver impacts on the traffic flow?

The disaggregation maneuver of the platoon can be performed one vehicle at a time, or two following vehicles can decelerate at the same time, one with half the deceleration of the other. The imposed deceleration on the first lane has an impact on the traffic flow, this impact increases as the deceleration value grows higher.

- *How many sudden brakes are performed among the vehicles behind the platoon?*

  Vehicles traveling behind heavy vehicles are not expected to keep an increased distance, considering the limited speed values and the possible intention to overtake as soon as the chance arises. If that is the case, the brake maneuver in response to a further deceleration of the truck ahead can be sudden and abrupt. This in turn could involve a shockwave propagation upstream the traffic flow.

- *How many vehicles change lane responding to the deceleration of the truck ahead? How many of them overtake the decelerating truck and re-enter the first lane?*

  The disaggregation maneuver is signaled like a simple brake from the following truck, then the vehicles behind the platoon can decelerate in response or decide to change lane. The lane changing maneuver can result in overtaking one of the following trucks or in overtaking the whole platoon, influencing the average speed of the performing vehicle and its accelerations and decelerations.

- *How smooth is the lane change maneuver performed by the vehicles behind the platoon?*

  The lane change maneuver can be smooth or abrupt in function of the deceleration value kept by the truck and of the traffic density on the other lane. More than one overtaking vehicle can perform this maneuver and impose decelerations on the other lane (especially if the lane changing maneuver is performed in a sudden and abrupt way).

Assessment instrument

The disaggregation maneuver can be investigated both through field tests and through modeling for which some literature works can also be considered [19]. Regarding the field tests the major issue could prove to be data collection from other vehicles; some of the data could be acquired through truck on-board sensors and cameras. Even if the test can’t be tailored to assess this maneuver impact, it could be used to record inputs regarding human behavior and interaction between platoons and surrounding traffic, useful to validate following models.

3.1.3 Research Question: How does the on-ramp interactions impact on traffic flow?

A platoon driving on the first lane at an on-ramp can hinder the entry of a vehicle that can't find a disposable gap before the acceleration lane ends. If that is the case, the vehicle stopped must enter the main road with a lower speed value, or drive on the hard-shoulder until its speed reaches the right value, then enter.

- *How many vehicles can't enter the main branch before reaching the end of the acceleration lane?*

  This number varies with the number of trucks of the platoon, the kept headway and the difference in speed. More vehicles that stops on the acceleration lane cause greater perturbations on the traffic flow of the main branch, having to enter with lower speeds and possibly causing other vehicles to decelerate too.

- *Which is the vehicle's speed once it enters the main branch?*

  Even if the entering vehicle doesn't stop on the acceleration lane but strongly decelerates, the disturbance on the main flow still occurs. In the same fashion, if the entering vehicles accelerates more to enter before the platoon, a potential benefit could affect Traffic Efficiency, due to the CACC capability to reduce the impacts of a possible braking action in the leading vehicle.

- *Does the vehicle accelerate in order to enter ahead the platoon or slows down to let it pass?*

  The behavior of the traditional driver regarding truck platoons should be investigated to assess what kind of impacts could affect the traffic flow.

- *How many vehicles proceeds on the hard-shoulders?*

  This dangerous behavior implies vehicles entering the main flow at random points across the road. These maneuvers can be more abrupt than usual and cause disturbances on the traffic flow.

- *How sudden is the passage from the acceleration lane to the main branch?*

  Having to enter the main road ahead a platoon, in limited times and spaces, can lead to more sudden maneuvers and resulting disturbances upstream. A vehicle that enters before the platoon, instead, could cause reduced disturbances thanks to the damping feature of the CACC system.

Assessment instrument

The on-ramp scenario can be investigated both through field tests and through modeling for which some literature works can also be considered, in [102] for example the modeling of the on-ramp scenario is studied. Regarding the field tests the major issue could prove to be data collection from other vehicles. The baseline scenarios that should be compared are the one in which the platoon adapts its dynamic-headway and the one in which the platoon dissolves before reaching the on-ramp area. Moreover, a scenario in which the platoon changes lane before the ramp should be considered and evaluated in its effectiveness.

3.1.4 Research Question: How does the off-ramp interactions impact on traffic flow?

A long platoon of trucks approaching an off-ramp area can easily hinder the exit maneuver of a vehicle on the left lane, representing a "wall of trucks" that forces other vehicles to decelerate, waiting for their chance to cross the right lane and take on the off-ramp (or worse, forcing them to resort to the next ramp to perform the exit maneuver). A vehicle that brakes on the left lane surely impacts the traffic flow, also its lane changing maneuver can be more sudden and have bigger effects.

- *How many vehicles give up in trying to take the off-ramp?*

  Imposing unwanted deviation on private vehicles leads to increased kilometers driven, a greater infrastructure usage and increased levels of congestion.

- *How does the exiting vehicle speed change in order to wait for the platoon to go on?*

  If the exiting vehicle must decelerate to wait for the platoon to have moved on, it imposes decelerations among the following vehicles in the left lane which certainly has an impact on Traffic Efficiency. The lower the speed reached, the greater these impacts.

- *How abrupt is the deceleration performed by the vehicle?*

  Especially in the short term, when traditional drivers still haven't acquired confidence with the Truck Platooning system, they can be taken by surprise and perform sudden decelerations that cause perturbation upstream the traffic flow.

- *How sudden is the lane change maneuver performed from the exiting vehicle, once the platoon has passed?*

  Especially in the short term, when traditional drivers still haven't acquired confidence with the Truck Platooning system, they can be taken by surprise and perform sudden lane change maneuvers once the platoon has moved on. That cause perturbation upstream the traffic flow on the right lane.

- *If the platoon dissolves in order to let other vehicles through, what impact does this maneuver have on the traffic flow?*

  As mentioned in paragraph 3.1.4, a disaggregation maneuver can impact the traffic flow, other vehicles' cut-ins could worsen or enhance the perturbation upstream the on-ramp area

Assessment instrument

The off-ramp scenario can be investigated both through field tests and through modeling for which some literature works can also be considered [89]. Regarding the field tests the major issue could prove to be the data collection from other vehicles. The baseline scenarios that should be compared are the dynamic-headway one and the disaggregation one. Also a scenario in which the platoon changes lane before the ramp should be considered.

3.1.5 Research Question: How much can the CACC-equipped platoons delay traffic jam creation? How much earlier the congestion is absorbed thanks to this?

The CACC, as mentioned above, proved to be able to absorb shockwaves thanks to the string stability achieved through wireless communication. This should have impacts on the traffic flow, especially accounting for levels of market penetration high enough that could absorb local perturbations, delay the creation of traffic jams and cause the traffic flow to go back to the decongested state earlier.

- *Beyond a certain percentage of truck platoons in the traffic flow, is the flow more stable?*

  Evaluations should assess when the benefits described above are achievable, if they truly are.

- *In congested traffic, does a certain percentage of truck platoons in the traffic flow anticipate the return to stable conditions?*

  The damping effects of CACC could absorb the flaws characteristic of the human driving among the traffic jam and foster an earlier recovery of regular traffic flow.

- *Does the kept headway between trucks varies beyond an established threshold?*

  A control algorithm that doesn't account for different acceleration and deceleration capabilities or the slope of the road, for example, can cause the loss of string stability and of the resulting benefits on the traffic flow.

Assessment instrument

The impacts of a certain CACC penetration can be investigated especially through modeling for which some literature works can also be considered [27, 55, 90], field tests can be employed to validate inputs and car following models used for the evaluations. The baseline scenarios that should be compared include different levels of market penetration and the case without truck platoons.

3.2 Safety

3.2.1 Research Question: Can the maneuvers performed by the platooning-equipped trucks and their interaction with other road users lead to dangerous scenarios caused by misread situations or lack of acquaintance with the new technology?

Other road users can wrongly guess the situation, especially in the short term when the technology market penetration is limited. This could lead to unpredictable behavior and, so, to unsafe or dangerous situations. Also, as stated in [102], approaching a standstill vehicle with high speeds while employing the constant time gap control strategy can result in collisions.

- *Do the formation and disaggregation maneuver cause sudden reactions or other potentially dangerous behaviors in the other road users?*

  Other road users can wrongly guess the situation, especially in the short term when the market penetration of the technology is limited. This, for example, could lead other road users to overtake a decelerating truck only to discover that there is a dissolving platoon ahead.

- *Are the cut-ins of intruding vehicles performed with reduced headways, to interrupt an overtaking maneuver or in sudden ways that could be dangerous for the truck platoon or the intruding vehicles?*

  An external vehicle can intrude a platoon for many reasons: the driver could not understand that the trucks are in formation, an overtaking maneuver was misjudged and must be interrupted, the platoon is too long to be overtaken as a whole etc. This makes the cut-in maneuver rather unpredictable and dangerous and should be hindered when the headway is not wide enough to guarantee safe intravehicular distances. Also, ramp interactions should be evaluated from the safety point of view.

- *Are the interactions at the ramp areas safety critical? Do light vehicles show unsafe behavior in order to enter from an on-ramp or to exit an off-ramp?*

  As mentioned in Chapter 2, a platoon of truck can represent a “wall” able to hinder the entrance or the exit of other vehicles in and from the main branch. This hindrance can be rejected by the most aggressive human drivers and can lead to unsafe maneuvers such as cut-ins carried out with extremely reduced values of TTC or by abrupt accelerations or decelerations (in order to exit the on-ramp ahead of the platoon or in order to let the platoon pass before engaging the off-ramp).

- *Does the platoon lane changing maneuver involve sudden braking or steering in the other vehicles? Are the gaps chosen by the leading vehicle* *driver to move on the targeted lane wide enough for the maneuver to be completed without disaggregation or TTC values lower than 1,5 s?*

To change lane, the platoon must have enough space on the other lane and enough time to perform the maneuver. Other vehicles could potentially find themselves in the chosen gap before the whole platoon has changed lane, this could potentially involve sudden braking or steering in order to avoid collision (especially in the short term, when the driver is less accustomed to this type of maneuvers). Also, the leading vehicle driver should consider every time the right gap in order to start the lane changing maneuver, if the gap proves to be shorter the maneuver should be interrupted and the platoon should divide itself. In these scenarios the number of sudden maneuvers could arise and lower intravehicular distances could occur.

Assessment instrument

The Safety evaluation should be done mainly through modeling or bibliographical review, in [23] for example some safety related parameters are described. Field tests or virtual testbeds can be employed to assess behavioral inputs to design appropriate car following models and safety critical scenarios. The data collected should also be relevant to investigate any incidents that may occur. In the event of a collision, data could be logged from at least 30 seconds before the event to 15 seconds after the event. [105]

3.2.2 Research Question: There are points, along the route, that could be potentially dangerous when travelled by a truck platoon or inadequate for its transit (e.g. tunnels, bridges)?

Along each route on which Truck Platooning is allowed, on every critical point the system operational performance should be assessed.

- *How does a platoon of trucks affect the bridge's structural behavior?*

  Bridges should be analyzed about their capacity to endure a more concentrated load (due to reduced headway between trucks and to the more precise axles alignment) but also checked to assess that the platoon system doesn't constitute additional dangerous situations.

- *How does a truck platoon handle potential communication delays that could happen, for example, inside a tunnel?*

  Tunnels should be analyzed considering their length and the probability of signal losses and platoon dissolutions; this case too should be checked to assess that the platoon system doesn't contribute to additional dangerous situations.

- *There are, along the route, other infrastructural/functional elements that weren't designed for the Truck Platooning system and that can constitute additional safety issues?*

  Considerations should be done, for example, about guard-rails and how they are not designed to contain a truck platoon, each of its design collision scenarios should be analyzed with a colliding truck platoon. Another safety-critical scenario concerns ramps, as mentioned above, for example, an entering vehicle that cannot merge before the end of the acceleration lane can drive on the hard shoulder or enter the main flow with reduced speed values. It should also be noted that many infrastructures across Europe have different features and can affect differently a truck platoon (e.g. The Spanish road network can reach slopes higher than the Italian one).

- *There are scenarios in which a platoon of truck is more or less prone to rear-end collisions?*

  Knowing that the CACC bypasses only human-reaction times, the rear-end collisions scenarios should be lower or the same as the ones in the human driven truck scenarios. The impact of communication delays or strong braking from vehicles ahead of the platoon should be evaluated, though, also considering the potential dangerousness of adhesion losses (caused, for example, by wet road surfaces or black ice).

Assessment instrument

The Safety evaluation should be done mainly through modeling or by the means of Checklists adjusted to account for the Truck Platooning system and the infrastructure elements considered. The data collected should also be relevant to investigate any incidents that may occur. In the event of a collision, data could be logged from at least 30 seconds before the event to 15 seconds after the event. [105]

3.2.3 Research Question: In a longer time horizon, if the following vehicles' drivers are allowed to rest during the travel, do the fatigue-related incidents involving trucks decrease?

As stated in [112], approximately 15-20% of commercial road transport crashes involve driver fatigue which means that completely granting the driving to the automation for the following vehicles could reduce fatigue and excessive workloads while still retaining high productivity levels. However, a reduction in trucks idle times resulting from a higher automation can lead to an increase of heavy traffic on the road and, therefore, to an increased risk.

3.3 Environment

3.3.1 Research Question: How does Truck Platooning impact on fuel consumption for the single truck?

- *How much fuel does a truck that travels in a platoon formation consume along the route? Is it more or less than the corresponding fuel consumption needed for the single trucks?*

  A truck that travels in a platoon consume less fuel and, therefore, has less impact on the environment. However, in the platoon on-the-fly scenario for example, to join a platoon the following truck must accelerate for a certain number of kilometers, consuming more. Besides, formation, disaggregation and cut-in maneuvers adversely affect fuel consumption.

- *How does driving in a platoon affects fuel consumption? How does this value depend on the headway value?*

  Lower headways decrease the air drag and the resulting fuel consumption. Also, higher headways allow more vehicles to cut-in, causing the platoon dissolution. For each feasible headway value, the corresponding fuel-related benefits should be assessed.

- *How do the platoon-related maneuvers (merging, disaggregation, cut-in, etc.) affect fuel consumption and how much do they hinder the environmental benefits?*

  Each of the maneuvers listed affect fuel consumption in different ways and quantities. The merging maneuver demands accelerations of the vehicles in order to reach the platoon leader. To dissolve a platoon, decelerations are required and, also, the merging maneuver must be carried out again. Besides, the possible presence of external vehicles between the trucks must be accounted for, implying an increased number of kilometers driven by the trucks in stand-alone mode. Cut-ins lead to braking, decelerations and platoon dissolutions and all the resulting negative effects of fuel consumption.

Assessment instrument

To assess fuel consumption for each headway value, also accounting for the weather-related quantities, track tests can be employed (as, for example, in [87]). To evaluate the impacts of other maneuvers on fuel consumption, field tests on public roads can be carried out to both evaluate quantities and to obtain behavioral inputs useful for modeling works (as in [7]). Moreover, in-platoon fuel consumption for each involved truck should be compared to the one achievable by the single truck on the same itinerary, loaded with the same gross weight.

3.3.2 Research Question: How does a certain market penetration of Truck Platooning affect the traffic flow stability, improving the infrastructure efficiency and decreasing the number of accelerations and decelerations?

- *How does the percentage of truck platoons among the traffic flow affect congestion and resulting emissions?*

  As mentioned in the second chapter, the CACC, thanks to intravehicular communication, can prevent human-related disturbances and absorb some of the shockwaves generated upstream by the traditional traffic, delaying congestion and, therefore, foster a more fuel-efficient traffic regime.

- *How much in advance does the congestion fade for a certain percentage of truck platoons among the traffic?*

  The CACC capability of absorb human-related driving shortcomings allows an earlier decongestion of the road branch for certain values of market penetration among trucks. It should be evaluated how different market penetrations, headways and spacing policies affect the return to a decongested traffic flow.

Assessment instrument

Having to account for certain levels of market penetration, still not achievable in the short term, only modeling instruments can be employed to assess the impacts of the CACC on the traffic flow regularity (as, for example, in [27, 90]) and resulting fuel savings.

3.4 User Acceptance

3.4.1 Research Question: How does the behavior of other road users change while approaching a truck platoon?

A new transportation system must be acknowledged by other road users and accepted. A platoon of trucks causes an obstruction in front of ramps, hinders lane changing or overtaking maneuver and, in general, represent an intimidating presence.

- *Do the drivers understand that the platoon is a whole element on the road?*

  In the short term, some drivers can wrongly guess the situation near them and see the aligned trucks as single entities. This scenario leads to a distorted situation awareness and to safety-related risks.

- *Do the drivers feel threatened by truck platoons? Do they carry more sudden maneuver when interacting with a platoon?*

  A platoon of heavy vehicles driving so close behind each other can scare other road users. Therefore, they can keep increased distances between them and the platoon (impacting mainly on Traffic Efficiency) or carry out overtaking maneuver both in a more prudent or abrupt way (impacting mainly on Safety). The abruptness of these maneuvers should also be evaluated near critical points on the infrastructure (e.g. near off-ramps an external vehicle can perform riskier cut-ins to be able to exit the main branch).

- *How do other trucks behave when behind a truck platoon?*

  Some truck drivers can be more inclined to align themselves to the platoon even when unequipped for Truck Platooning, increasing its length and associated risks. Other truck drivers, instead, can find the 80 km/h speed to be too restrictive and overtake the platoon. This maneuver can last too much and hinder the traffic flow when carried out improperly (when the speed difference is low and the platoon length is high). In fact, the gap kept by the platoon is not wide enough for the overtaking truck to cut-in back in the first lane.

- *Is a platoon signaled, for example, with specific marking on the trailers acknowledged more by other road users?*

  Signaling a platoon can help other road users to identify the situation clearly. Having an improved situation awareness helps them make decisions safely, efficiently and without doubts that could diminish their user acceptance towards the new transportation system. The signaling can be also done by the means of V2V communications, this solution seems more efficient (maneuvers could be carried out jointly) but is also bound to market penetration and, therefore, not suited for the short-term scenario. Nevertheless, the V2V solution should be evaluated too.

3.4.2 Research Question: How do the drivers behave when part of a platoon? Do they comply willingly with the imposed driving regime?

Being part of a platoon implies that the single truck driver must cede some of its authority to the platoon leader. This shift in control should not be perceived as a threat, it is important that the drivers cooperate for the system to function properly. Therefore, a certain level of trust must be achieved both towards the reliability of the automated function and the trustworthiness of the other truck drivers involved. It is also important that the drivers perceive the Truck Platooning system as an enhancing element to their driving task and not as a nuisance.

- *Do the drivers feel threatened by the reduced headway values?*

  Reduced headway values can induce, among the drivers, a feeling of danger or a reduced comfort while driving (with a consequent increase of the workload associated with the driving task), as suggested, for example, in [39]. This, in turn, can reduce the level of user acceptance among truck drivers, strongly hindering the deployment of the system in the short term.

- *Do the drivers accept the driving regime imposed by the leading vehicle and how the maneuvers are carried out?*

  Being part of a platoon means that the longitudinal control is no more entrusted to the drivers of the following vehicles, this means that they must find acceptable the speed kept by the leading vehicle and the carried-out maneuvers (that should be perceived simultaneously as safe and efficient).

- *Do the drivers perceive the system as a threat to their job?*

  It is important, in the short term, that the driver doesn't perceive the system as a threat and is motivated to exploit its potentialities, instead.

- *Do the drivers fully understand what the system does and how it works?*

  An enhanced understanding of how the system works and what does it do should lead to an improved situational awareness which, in turn, translates in higher levels of user acceptance among the drivers.

Assessment instrument

To assess User Acceptance, the most efficient tools are Surveys presented after field tests and large-scale demonstrations.

4 Jointed impacts of Truck Platooning and C-ITS

In this chapter guidelines for the evaluation of the jointed implementation of Truck Platooning and Day 1 C-ITS services will be presented. Again, the evaluation will concern the following impact areas:

- Traffic Efficiency
- Safety
- Environment
- User Acceptance

Specifically, how both the systems interact in order to maximize their benefits will be analyzed, leaving to other works the impacts evaluation of the single systems.

The scenarios considered will mostly concern mono-brand truck platoons on public roads (specifically, highways), to focus on the short and middle-term impacts based on the most likely implementation defined in chapter 2 for Truck Platooning. Regarding the C-ITS services, the implementation scenarios will be the ones defined during the European activities of C-Roads for the identified use cases. These guidelines will be provided only for the ones among the use cases judged relevant when referred to Truck Platooning in the short and medium term. This means that, for example, the service group "Functional Description of Traffic Light Maneuvers & Road and Lane Topology" is not going to be studied in the present Ex Ante Evaluation because judged relevant only in medium/long time horizons (on the basis of the Chapter 2 bibliographical review). In the short term, in fact, truck platoons shouldn't travel in urban areas and approach signalized intersection. Clearly, this doesn't mean that the jointed implementation of this service group with Truck Platooning doesn't involve relevant impacts on Traffic Efficiency, Safety, Environment and User Acceptance.

Besides, the definition of some services is still being developed in the C-Roads activities and is seen as premature to provide a methodological approach to assess the impact for scenarios still changeable. That is the case of use cases and services like Emergency Electronic Brake Light, Shockwave Damping or the Emergency Vehicle Approaching. Also for the Road Works Warning service, for example, many use cases have still to be clearly defined and is, then, judged as overhasty to define research and sub-research questions for them.

This chapter, therefore, focuses on the services and use cases judged relevant in their jointed implementation with Truck Platooning among the Day 1 services that are being defined by the C-Roads Platform. This selection has been conducted on the basis of the extensive bibliographical review and with the following objective: define an evaluation methodology able to guide evaluators in designing field tests and modeling works in the next future to assess the impact of two innovative and still evolving transport systems (Truck Platooning and Cooperative ITS). This work, then, isn't aimed to define all the possible joint impacts and surely can be expanded to consider the remaining

C-ITS Day 1 services and the services of cooperative mobility foreseen for broader time horizons (Day 1.5 and Day 2 services, for example).

For each one of the services judged relevant in function of what stated above, the most likely scenarios will be considered and the inputs and outputs required to assess the impacts will be highlighted. The followed approach is based on “Research and Sub-Research Questions” as presented in the Evaluation and Assessment Plan [129]. This methodology, applied to the jointed implementation of both Truck Platooning and C-ITS services, produced the following outputs for each analyzed Use Case:

- One or more Research Questions, aimed at assessing when the C-ITS service allows the platoon to maintain its formation, analyzing how to quantify the number of added kilometers to the travel in platoon formation. Thus, the effect of the C-ITS service on the smoothness of platoon maneuvers and on their safety is also investigated. Besides, the increased efficiency of Truck Platooning is expected to impact on the surrounding traffic flow and, therefore, on the C-ITS service outputs.
- Sub Research Questions such as “Does the C-ITS service allow the platoon to maintain its formation?” or “The platoon changes its behavior in response to a C-ITS service?” The changes of the parameters that characterize the service functioning/platoon driving are investigated for each relevant scenario; possible data requirements are mentioned.
- Suggested methods and tools to quantify the impact of the jointed implementation on the impact areas listed above, referring to the bibliographical review in chapter 2 and to the C-Roads documents describing the C-ITS services. Parameters possibly needed as output and how to measure them will be mentioned.

This work aims to tackle a need arising because both Truck Platooning and C-ITS services are not yet implemented on public roads (with some exceptions about C-ITS projects and corridors), it is not possible, then, to obtain numerical results bound to their jointed implementation. Moreover, about this subject, a bibliographical review that could be used to assess the jointed impacts is still lacking. Therefore, in this chapter, a similar approach to the one followed for chapter 3 will be employed, referring to the separate bibliographies and states of the art about Truck Platooning and Cooperative Mobility.

How to investigate in depth each scenario, which data requirements to meet and output indicators to measure should be decided by the evaluator as function of the test specificities and of the regional features. Besides, it should be noted that these evaluation guidelines have been designed to be applicable in general scenarios and are not referred to specific field tests or modeling works carried out in the C-Roads Italy activities (during which there will certainly be field tests but not every subject listed in the following paragraph will be evaluated). Finally, it should be highlighted that, generally, an Ex-Ante report draws the expected impacts from the available bibliography or through modelling works, identifying the state of the art. The present Ex-Ante in the chapters 3 and 4 goes a little beyond a traditional Ex Ante and draws a first methodology on the basis of which the future evaluation works can be designed (including both field tests and modeling works), defining the relevant parameters and the hypotheses that could be employed to quantify the impacts of the implementation, on public roads, of both Truck Platooning and the majority of the Day 1 C-ITS services. In fact, in this second part of the Ex-Ante, data requirements and the indicators that could be obtained to study the impacts are reported for each implementation scenario and impact area, laying also the foundation for the design of the Ex Post evaluation (that will be carried out in the next years as another one of the activities within C-Roads Italy).

4.1 Road Works Warning

Service description

On the basis of what is stated in [108], the following considerations can be made. This service is intended to provide warnings to road users approaching a road works, mobile or static, short-term or long-term. The use cases considered in their joint implementation with Truck Platooning are:

- closure of part of a lane, whole lane or several lanes;
- alert planned road works – mobile.

About the “Alert planned closure of a road or a carriageway”, no guidelines will be provided, it is still worth noticing that, for an optimization model like the ones described in 2.2, the addition of these information in the algorithm could involve additional benefits, especially in fuel savings.

The benefits that the service alone is meant to achieve are mainly an increased safety and reduced number of collisions near road works, besides improvements in Traffic Efficiency and Environment could also be obtained.

It should be noted that for both the use cases defined above it seems useful to broadcast the information to each truck, not only to the leading vehicle one, and let it show on the HMIs. That is because a lane changing maneuver must be accomplished and an increased situation awareness for each driver is beneficial. For other use cases this consideration is not straightforward and in each scenario the amount of information granted should be evaluated.

Moreover, the digitalization of information related to roadworks can be more near than usually thought. In fact, other activities towards the digitalization of the infrastructure are being carried out within the UMneo project, for example in the Rheinland-Pfalz the information concerning all roadworks are going to be digitalized and made available to road users [127].

4.1.1 Closure of part of a lane, whole lane or several lanes

The drivers know, by the means of the C-ITS service, of a lane closure due to roadworks in advance. This way they can change lane earlier and in a smoother way, making the traffic flow readier to approach the critical stretch. On the basis of Chapter 2 (Truck Platooning – Bibliographical Review), the lane change maneuver can be considered critical for heavy vehicles platoons both from Traffic Efficiency, Environmental and Safety points of view.

4.1.1.1 Traffic Efficiency

Research Question: Does the information forwarded in advance change the platoon behavior in a way that is beneficial for the whole traffic flow?

A roadworks constitutes a critical stretch on the road branch, across which vehicles travel with an increased density and reduced velocities. Thus, congestion arises faster and propagates upstream easily. In such a critical scenario an element long and intrusive like a truck platoon can worsen the congestion level and be forced to dissolve, losing all the benefits deriving from the in-formation driving and possibly finding itself unable to reform for many kilometers downstream the roadworks. An earlier notification about the lane closure can, possibly, let the platoon pass without dissolving or, at least, bring forward the dissolution in order to minimize the impacts of this maneuver on the already inhibited traffic flow. Even when the notification is set to arrive when passing the first roadworks signal, a major awareness should promote similar effects.

- *Does the information forwarded in advance or in a more intrusive way allow the platoon to change lane earlier and to keep its formation? Does the lane change point vary?*

  Knowing the lane closure ahead, the driver of the leading vehicle can start searching for gaps on the other lane earlier and has increased chances to find a gap wide enough for the whole platoon to fit in. Avoiding the platoon dissolution eliminates the negative impacts of the maneuver on the traffic flow and, also, involves just one lane changing maneuver instead of a maneuver for each truck (and, then, a perturbation on the traffic flow for each truck).

- *Is the platoon lane changing maneuver smoother thanks to the received information?*

  Knowing of the lane closure in advance grants to the leading vehicle's driver the possibility to search for a gap in advance which means that the lane change maneuver can be accomplished in a more efficient way. A smoother lane change maneuver means lower perturbation on the upstream traffic flow which is especially important while approaching a bottleneck like the roadworks one.

- *The platoon dissolution is accomplished in a more efficient way? The platoon dissolves with sufficient advance to let some of the single trucks change lane before reaching the roadworks?*

If the platoon is unable to change lane, despite knowing earlier or having an increased awareness about the lane closure, it should dissolve before entering the roadworks area (is unrealistic to imagine a lane change maneuver for the platoon as a whole, accomplished just before the roadworks entrance, in a congested state of the traffic flow). Beyond a certain distance, the platoon should dissolve in order to let some of the trucks change lane before reaching the roadworks, this certainly has a negative impact on the traffic flow but is preferable rather than having three or four trucks queued just before the roadworks entrance section.

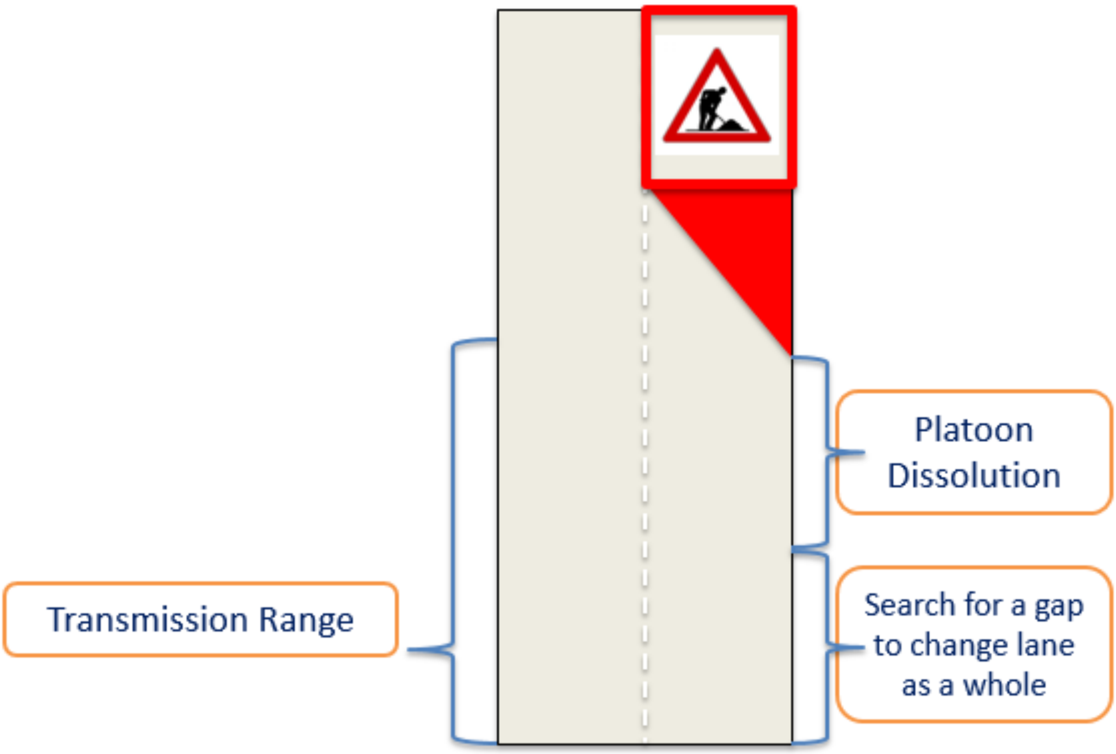

Figure 7 - RWW Lane Closure

It should be noted that, if the platoon algorithm can calculate the space needed for the disaggregation, the information granted by the service could allow the optimal dissolution distance evaluation.

- *Is the platoon speed more homogeneous?*

Receiving information about the lane closure and especially the suggested speed limit could promote a smoother driving for the platoon and reduce its impacts on the surrounding traffic flow, lowering the number of sudden braking and, therefore, of the perturbations propagated upstream.

- *Does an increased number of platoons passing through the work zone in formation enhance the traffic flow?*

  Avoiding the platoon disaggregation means that the CACC shockwave damping effects are still exploited across the roadworks length, easing the bottleneck congestion and fostering an earlier return to the decongested state.

Assessment instrument

To assess the jointed impacts, both field tests and modeling works can be employed. When field tests are designed, no roadwork should be encountered twice by the drivers, to avoid results influenced by any previous acquaintance with the situation. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. Examples of this kind of specifications can be found in the dedicated C-Roads documents [108].

4.1.1.2 Safety

Research Question: With the information forwarded in advance or in a more intrusive way, are the platoon maneuvers carried out in a safer and more reliable way?

An improved situation awareness about the roadworks position and its characteristics allows the platoon to change lane or dissolve in a smoother way. Also, avoiding the scenario in which the full platoon is stuck just before the bottleneck section decreases the likelihood of abrupt maneuvers performed by the truck drivers in order to change lane.

- *Is the platoon lane changing maneuver smoother thanks to the received information?*

  Receiving information about the lane closure grants to the leading vehicle’s driver the possibility to search for a gap in advance which means that the lane change maneuver can be accomplished in a smoother way. A smoother lane change maneuver means increased TTC values and lower collision risks.

- *Is the platoon speed more homogeneous?*

  Receiving information about the lane closure and especially the suggested speed limit could promote a smoother driving for the platoon and reduce the chances of a sudden braking and, therefore the risk of rear-end collisions with surrounding vehicles.

- *Does an L3 platoon disaggregates if the received information about the roadworks topology could hinder the lateral control (e.g. unsuitable lane markings, road cones etc.)?*

  In the scenarios which concern a level of automation L2 (or higher), lane marking detection or cone recognition are essential for the system to work [103]. If the roadworks hindered the signage, somehow, and this information is broadcasted by the means of X2V communication, the automation itself can fall back on the drivers for them to retake the controls. This would promote an earlier return of the drivers in the driving loop and a safer take-over transition. As stated in [105], there are doubts among different stakeholders about the capability of a truck platoon to navigate road works safely when the need to cross a solid line or follow non-standard methods of delineation (cones barriers, temporary marking and masking tapes etc.) arises. A way to tackle this issue could be exploiting the information contained in DENMs such as traces and eventHistory, to allow an L3 platoon to drive through roadworks [125].

Assessment instrument

To assess the jointed impacts, both field tests and modeling works can be employed. When field tests are designed, no roadwork should be encountered twice by the drivers, to avoid results influenced by any previous acquaintance with the situation. Field tests should focus in assessing safety-related parameters bound to human behavior while the modeling works should obtain values for the safety-related output like TTC and BTN, as function of the different human behavioral models and implementation scenarios. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. If the OEMs design the HMI to show only some of these information, which ones are displayed and when must be specified.
Examples of this kind of specifications can be found in the dedicated C-Roads documents.

4.1.1.3 Environment

Research Question: Does the information granted by the service promote a more efficient driving both from platooned trucks and human-driven vehicles interacting with the platoons?

The same scenario described in the Traffic Efficiency research question (paragraph 4.1.1.1) is applicable for the Environment impact area. An earlier notification (or a more intrusive and detailed one) could lead to an increased number of platoons able to pass the roadworks without dissolving themselves. As confirmed by the literature review, increasing the number of kilometers driven in platoon formation leads to major fuel savings and lower emission levels. Besides, keeping the platoon together before and after the bottleneck section allows the CACC to perform its shockwave damping feature and foster an earlier return to the decongested state. Also, an increased situation awareness can ease the lane changing maneuver performed by the platoon and reduce its negative effects on the surrounding traffic flow.

- *Does the service allow a greater number of platoons to keep their formation?*

  Knowing about the lane change allows the leading vehicle driver to start searching for a gap on the other lane as soon as he gets the information. If the information is broadcasted with a sufficient range or granted by a service provider, the platoon is more likely to perform the lane change maneuver as a whole, passing the roadworks section without the need to dissolve. Allowing the platoon to pass through the roadworks in formation means that each truck involved still retains a reduced fuel consumption. Moreover, not dissolving the platoon leads to only one lane change maneuver needed, while separating the trucks means that each one of them has to change lane, impacting the surrounding traffic flow with induced shockwaves upstream and, thus, an increased fuel consumption.

- *Do the smoother lane changes have an impact on the surrounding traffic flow and on shockwaves creation and propagation?*

  The need to change lane for two or more heavy vehicles together can have negative impacts on surrounding road users, possibly imposing more abrupt braking due to the increased spaces needed for the platoon to change lane as a whole. Performing the maneuver in advance, not in close proximity to the bottleneck section and when the traffic is less congested, means wider gaps and smoother maneuvers. Lowering both the number and the severity of the shockwaves propagated upstream implies a more fuel-efficient driving and less accelerations and decelerations along the traffic flow.

- *Research Question: Does the CACC system promote an earlier return to the decongested state, lowering the emissions due to the bottleneck caused by the roadworks?*

  A platoon allowed to travel in formation across the roadworks exploits the CACC capability to dampen shockwaves (confirmed by the literature review in chapter 2). This means that, for each extra platoon that the Use Case manages to let through compared to the baseline scenario, a positive impact on the flow state and, therefore, on the level of emission can be achieved. The baseline scenario is defined in assessment instrument.

Assessment instrument

Assess the environmental impacts, especially in field tests where few platoons are employed, can be extremely challenging. As general rule, during a field test, the same platoon features (headway, speed values) should be kept for each passage across the roadworks, also the drivers should cross each single roadwork area only once because knowing the exact position of the road works would influence the driver behavior during a second crossing. Yet, drivers should be familiar with the C-ITS service to avoid measurements during learning phase (behavior of informed driver should be compared with an uninformed one). Again, field tests could be designed to obtain the behavioral inputs that a model can employ to assess fuel consumption and, then, environmental impacts. The baseline scenarios considerable are the one in which a platoon doesn't receive the Use Case information and the one in which the same number of trucks passes through the roadworks by themselves.

4.1.1.4 User Acceptance

Research Question 1: Does having the information earlier improve the situation awareness among the drivers, easing the lane changing task and improving the feeling of safety and system reliability?

Driving with reduced headway can hinder the field of view for the following vehicles' drivers. Despite many solutions consider the view of the front camera on the leading vehicle to be broadcasted to the following vehicles, in a long platoon the following vehicle driver could feel threatened during a lane changing maneuver (especially when abrupt or carried out with small gaps on the other lane). A smoother lane changing maneuver can improve the feeling of safety, while information about the situation ahead, broadcasted by the C-ITS service, lead to an improved situation awareness. Besides, avoiding the platoon dissolution by the means of the C-ITS service can reduce the number of episodes in which the trucks find themselves to be stuck on the right lane, just before the bottleneck section, and unable to change lane. In this kind of scenario, the trucks ahead will travel earlier the roadworks while the following vehicle drivers could fell themselves left behind (a mainly critical scenario when the multi-brand platoons are considered).

Assessment instrument

To assess User Acceptance, the most efficient tools are Surveys presented after field tests and large-scale demonstrations.

Research Question 2: Is the message delivered by the service clearly displayed on the platoon HMI? Is it clear how both the platoon and the single driver should behave?

It is important that the message designed for a generic vehicle, equipped for the message reception, doesn't turn out to be confusing for a driver possibly not in the driving loop (L3 platoon), with reduced field of view and travelling in a platoon. It should be clear if he must do something apart from the lateral control task or if only the platoon leader should drive accordingly to the event signaled ahead. If the OEMs design the HMI to show only some of the received information, which ones are displayed and when must be specified.

Assessment instrument

To assess User Acceptance, the most efficient tools are Surveys presented after field tests and large-scale demonstrations. It is important that the broadcasted message doesn't result confusing on a platoon-dedicated HMI and that every driver understands who, inside the platoon, must react.

4.1.2 Alert planned road works – mobile

The driver knows in advance about the neutralization of part of a lane or a lane closure due to mobile work sites, the main objective achievable through this use case is an increased safety for mobile roadworks that are usually "lighter" in terms of protection and signaling. Other desired behaviors are an adaptation of the kept speed before reaching the roadworks and a change of lane more efficient if needed and possible (it should be noted that the adaptation of the longitudinal and lateral controls can be achieved if the C-ITS message effectively broadcasted contains enough information).
Because the scenarios are pretty similar to the ones defined in 4.1.1, the considerations presented in that paragraph can be considered valid for this use case too.

4.2 In Vehicle Signage (IVS)

Service description

On the basis on what is stated in [109], the following considerations can be taken. This service is intended to inform road users on actual, static or dynamic road signs as indicated on the physical road signs along the road, encountered by the equipped vehicles. Additional virtual information (VMS or free text) can be transmitted to the vehicles too, target information to specific vehicle types can be implemented. The IVS service is carried out through I2V communication (started from Service Providers or Traffic Control Centers, for example).
The use case considered in its joint implementation with Truck Platooning is:

- Dynamic Speed Limit Information

The benefits that the service alone is meant to achieve are mainly an increased awareness about road signage, providing the information directly in the vehicle where it can be displayed until the validity lasts. For Truck Platooning this communication can support the sensor-based information gathering and reduce the issues bound to the limited field of view for the following vehicle drivers, like mentioned in the chapter 2. Also, the service can broadcasts signage-related information earlier, resulting in better adaptation to current regulations and traffic conditions.

It should be noted that for this service it should be evaluated which information are relevant only for the leading vehicle and which also for the following vehicles. For example, the current speed limit could be of little usefulness for the following vehicle drivers. A dynamic speed limit, instead, could avoid misunderstanding among the drivers, making the following vehicle drivers aware of the reason that causes the leading vehicle to go slower than expected.

About the Embedded VMS "Free Text" use case, no guidelines will be drafted because judged similar in impacts to the single truck scenario (on the basis of the bibliographical review of Chapter 2). It should be highlighted, though, how a more precise and spread information about travel time can enhance the "Just in Time" delivery for a platoon of trucks and information about available parking spaces on highway rest areas can help the drivers in planning rest times (it should be noted that a full platoon arriving at a rest area can find insufficient parking spaces for all the trucks involved).

Regarding the use case Other Signage Information, some consideration can be made. The service carried out through this use case broadcasts signage information such as bans on overtaking or lane advice/closures (in general, static and dynamic traffic regulations and traffic advice are indicated on the basis of the strategies adopted by the TCC). The information explicitly included in the use case description in [109] are: speed advice and adaptation, overtaking prohibition, lane advice and information about closed lanes and potentially dangerous event ahead.

These messages have impacts rather similar to the ones defined in the other paragraphs of this chapter (e.g. lane closure is analogous to what has been already stated in 4.1.1), therefore won't be analyzed here in 4.2.

Both Embedded VMS "Free Text" and Other Signage Information could lead to an increased situational awareness in the drivers of the following vehicles, tackling the issue of the reduced field of view and displaying information useful in case of take-over.

4.2.1 Dynamic Speed Limit Information

A dynamic speed limit recommended by the road manager or by an external service provider is broadcasted to the vehicles. This should lead to a safer driving behavior and to potential environmental benefits. It is worth noticing that the message and the speed limit can be targeted to a specific vehicle type (e.g. Heavy Goods Vehicles). Besides, in [109] is stated how the IVS information shall be displayed to the driver early enough, which could be as soon as useful, in order to maximize the related benefits.

4.2.1.1 Traffic Efficiency

Research Question: Does the platoon drivers adapt their behavior because of the warnings/information given by the service?

The drivers are informed, continuously and in advance, on a suggested speed limit. In a truck platoon the leading vehicle driver adjusts the speed value to follow the suggestion granted by the service. This value can be updated continuously according to the changes in the downstream traffic flow and can prevent the platoon to reach queues or traffic jams and lose the potential effects of the CACC on the traffic flow stability. It should be highlighted, indeed, what has been explained in chapter 2: a CACC-equipped platoon can dampen the shockwave propagation upstream as long as it doesn't find itself in a totally congested section where its speed value drops to nearly zero. In that case the platoon-related benefits on the traffic flow are limited to an earlier recovery to the decongested state. Thus, preventing the platoon from being stuck in a queue or before a traffic jam leads to an increased traffic efficiency that grows with the market penetration of the Truck Platooning system.

- *Is the driver's speed (more) compliant with the suggested speed limit?*

  Having the suggested speed limit continuously broadcasted on the HMI could have an impact on the behavior of the leading vehicle driver and, therefore, on the kept speed value. Besides, having this suggested speed limit updated as soon as the downstream traffic conditions change means a readier adaptation when compared to the punctual information granted by the Variable Message Signs, for example. Both these effects should prevent the platoon from finding itself stuck in the congested traffic and exploit the CACC-related benefits mentioned above (or at least the moment in which the platoon is stuck should be delayed, prolonging the benefits of the CACC on the traffic flow stability).

Assessment instrument

To assess the jointed impacts, both field tests and modeling works can be employed. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. If the OEMs design the HMI to show only some of these information, which ones and when are displayed must be specified. Examples of this kind of specifications can be found in the dedicated

C-Roads documents [109]. During a field tests the CACC-related benefits could prove to be difficult to assess but still the results can be used to define the behavioral inputs that a model can employ to evaluate the effects on Traffic Efficiency. The baseline scenarios considerable are the one in which a platoon doesn't receive the Use Case information at all and the one in which the information is granted by the means of Variable Message Signs. Besides, different scenarios including different levels of market penetration could be considered in the modeling works.

4.2.1.2 Safety

Research Question: Does the information forwarded earlier and/or in a more continuous way promotes a smoother and safer driving for the platoon?

Avoiding speeding and potentially reaching the end of the queue with an already decreased speed could lower the number of rear-end collision scenarios. The actual impact of the use case on safety should be evaluated keeping in mind that the leading vehicle should be generally equipped at least with a Forward Collision Warning system and the Emergency Brake Assist that should prevent rear-end collision between the leading vehicle and the one preceding the platoon (or lower its severity). Overall the safety impacts of this Use Case are pretty much similar to the ones achievable by a single truck receiving the same message.

4.2.1.3 Environment

Research Question: Does the information forwarded earlier and/or in a more continuous way promote a smoother driving, with fewer accelerations and decelerations and consequently lower emission levels? Does the information prevent the truck platooning from being stuck in the congested traffic?

Receiving the suggested speed limit earlier allows the platoon to adapt its speed in a smoother way and achieve regular driving for an increased number of kilometers. Besides, for a truck platoon, to travel with a slightly reduced speed for an increased number of kilometers is surely more fuel efficient than travel with normal speed but ending up getting stuck in behind a queued, with speeds closer to zero and unable to exploit the aerodynamic benefits of Truck Platooning.

- *Is the driver's speed (more) compliant with the suggested speed limit?*

  A message continuously forwarded inside the vehicles leads to an increased speed adaptation, thus limiting the number of accelerations and decelerations and, therefore, the emissions of two or more heavy vehicles.

- *Do the informed platoons actually avoid getting stuck in traffic jams? If not, the informed platoons reach later the congested sections and are stuck for lower time?*

Until the platoon's speed doesn't drop below 50 km/h [106], aerodynamic benefits are achieved and fuel consumption is reduced. This means that delaying or avoiding the traffic jam or the queue by the means of a reduced speed value can potentially result in lower emissions generated from the platoon.

- *How does having slower platoons driving in formation upstream the queue impact on the congestion recovery?*

  As mentioned above, if a sufficient number of platoons drives upstream the congested section, the shockwave damping effect of the CACC can ease the traffic flow conditions and lower total emissions on the road branch.

Assessment instrument

Assess the environmental impacts on the traffic flow, especially in field tests where few platoons are employed, can be extremely challenging. It should be possible to evaluate the fuel savings for the single platoon, though. To evaluate broader impacts on the whole traffic flow modeling works should be considered, instead. The baseline scenarios considerable are the one in which a platoon doesn't receive the Use Case information at all and the one in which the information is granted by the means of Variable Message Signs. Also, different scenarios including different levels of market penetration could be considered in the modeling works.

4.2.1.4 User Acceptance

Research Question: Is the message delivered by the service clearly displayed on the platoon HMI? Is it clear how both the platoon and the single driver should behave?

It is important that the message designed for a generic vehicle, equipped for the message reception, doesn't turn out to be confusing for a driver possibly not in the driving loop (L3 platoon), with reduced field of view and travelling in a platoon. It should be clear if he must do something apart from the lateral control task or if only the platoon leader should drive accordingly to the event signaled ahead.

Assessment instrument

To assess User Acceptance, the most efficient tools are Surveys presented after field tests and large-scale demonstrations. It is important that the broadcasted message doesn't result confusing on a platoon-dedicated HMI and that every driver understands who, inside the platoon, must react. If the OEMs design the HMI to show only some of these information, which ones are displayed and when must be specified.

4.3 Hazardous Locations Notification

Service Description

On the basis on what is stated in [110], the following considerations can be made. This service is intended to provide warnings to road users approaching a series of potentially hazardous events on the road. The information delivered concerns the location, the type of the hazard and, if available, also the duration of the event. The use cases considered in their joint implementation with Truck Platooning are:

- Accident Zone
- Traffic Jam Ahead
- Slow or Stationary vehicle
- Weather Condition Warning
- Temporarily slippery road
- Animal or person on the road
- Obstacle on the road

Only for this service's use cases, a clustering approach is going to be followed and the use cases sharing similar research questions related to the Truck Platooning system are going to be examined in the same paragraph. Moreover, the use case "animal or person on the road" is not going to be considered because judged similar in impacts to the single truck scenario.

The benefits that the service alone is meant to achieve are mainly bound to safety, an increased attention, adaptation of the driving speed and lane changing (if needed) are the expected behavior among informed road users. It should be noted that, for this service's use cases, some of the information can be broadcasted only in the leading vehicle (this decision should be based on a comparison between the benefits bound to an increased situational awareness and the flaws related to a confusing driver-machine interface and an increased workload).

4.3.1 Cluster 1: Accident Zone – Slow or Stationary Vehicle – Obstacle on the road

The drivers know, by the means of the C-ITS service, of a dangerous situation along the road in advance. If the information is detailed enough, the platoon can adapt its speed or even change lane in advance and avoid being stuck just before the signalized section. As mentioned before, an earlier and smoother lane change maneuver results in lower impacts on the traffic flow. In fact, on the basis of Chapter 2 (Truck Platooning – Bibliographical Review), the lane change maneuver can be considered critical for heavy vehicles platoons both from Traffic Efficiency, Environmental and Safety points of view. Also, this way, some scenarios in which the platoon, stuck behind an accident zone for example, must dissolve in order to change lane are potentially avoided. The same can be said for overtaking maneuvers carried out to surpass a slow vehicle with technical difficulties.

4.3.1.1 Traffic Efficiency

Research Question: Does the information forwarded in advance change the platoon behavior in a way that is beneficial for the whole traffic flow?

Informing the leading vehicle's driver of the incoming dangerous situation allows him to search earlier the other lane for gaps wide enough to accommodate the whole platoon. This should lead to smoother maneuvers and decreased impacts on the surrounding traffic flow. Even if the information is not detailed enough to let the leading vehicle's driver change lane in advance (or the traffic density hinders such maneuver), knowing about the accident zone or the stationary vehicle leads to smoother braking and, therefore, decreased shockwaves propagated upstream.

- *How does the lane change point vary (if the lane of the event is specified)?*

  Knowing about a slow or stationary vehicle can help the platoon to overtake such vehicles in advance, avoiding sudden steering and resulting negative impacts on the traffic flow upstream. The same considerations can be made about an accident zone if the whole carriageway isn't involved.

- *Does the average speed decrease?*

  The increased awareness about a potentially hazardous event leads to lower speeds on the road and, potentially, to fewer sudden and relevant braking when the event is reached, thus obtaining less perturbations upstream.

- *Does the service avoid the platoon dissolution?*

  Knowing about a slow vehicle ahead should make easier the lane change maneuver, avoiding the scenario in which the platoon finds itself stuck behind a broken-down vehicle and must dissolve to overtake it, one truck at a time. As mentioned in the paragraphs above and in chapter 2, the disaggregation maneuver can have negative impacts on Traffic Efficiency, besides having potentially three or four trucks overtaking a slow vehicle means four lane change maneuver perturbing the upstream traffic flow. In general, accident zones and slow or stationary vehicles can easily impact on the traffic flow, temporarily worsening the capacity of the road. If the C-ITS service fosters the regularity of the truck platoon driving, the platoon in turn can absorb the shockwave propagating upstream, delaying or avoiding congestion.

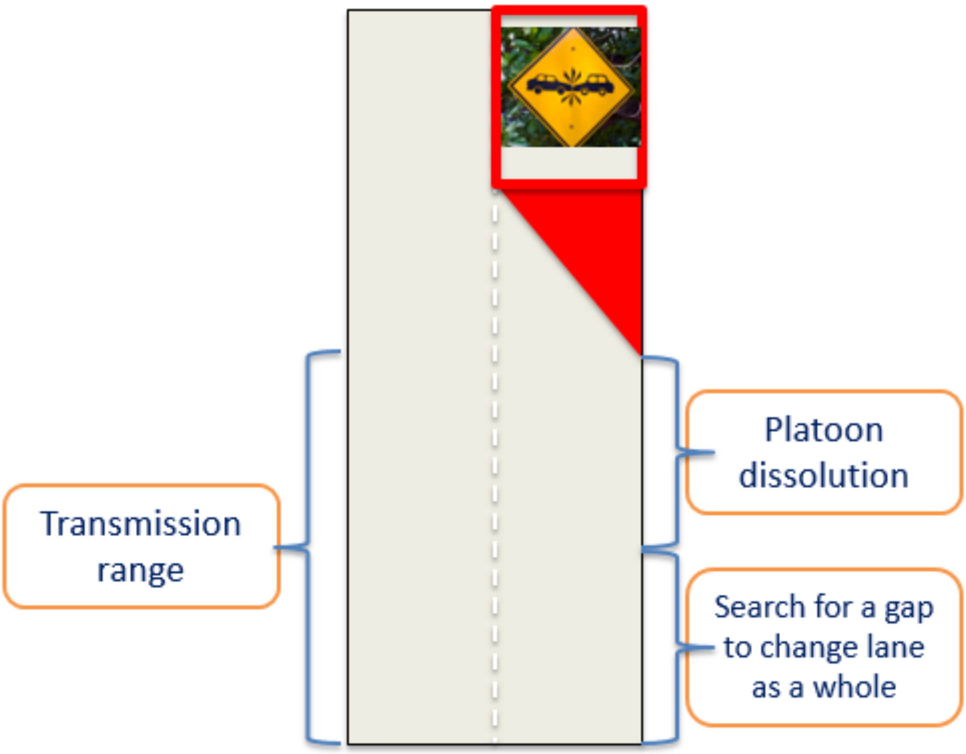

Figure 8 - HLN - Accident zone

Assessment instrument

To assess the jointed impacts, both field tests (to evaluate the drivers' behavior) and modeling works can be employed. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. If the OEMs design the HMI to show only some of these information, which ones are displayed and when must be specified. Examples of this kind of specifications can be found in the dedicated C-Roads documents [110]. Also, each use case included in the cluster should be evaluated separately.

4.3.1.2 Safety

Research Question: With the information forwarded in advance or in a more intrusive way, are the platoon maneuvers carried out in a safer and more reliable way while approaching the dangerous event?

The forwarded information should allow the platoon to reach the dangerous event already disaggregated or on one of the free lanes. Even if that is not the case, an increased situational awareness should promote slower driving and, therefore, smoother braking maneuvers. The lane change maneuver can be carried out in a smoother way too, lowering the related risks.

- *How do the instant speed fluctuations change?*

  The leading vehicle's driver that knows about the dangerous event ahead starts decelerating earlier, in a more conscious way.

- *Is the lane change maneuver smoother?*

  When the message content is precise enough, the leading vehicle driver knows about the need to perform a lane change maneuver in advance which means that the probability of finding sufficient gaps increases. A wide gap should imply greater values for TTC and BTN and, therefore, less safety-critical scenarios during the maneuver.

- *Does the service decrease the number of scenarios in which a truck platoon suddenly finds itself stuck behind a slow or stationary vehicle?*

  Trucks, generally, have lower acceleration capabilities. An overtaking maneuver involving a whole platoon, starting from speed values almost null, can be dangerous, especially on a two-lane carriageway, and involve sudden braking from other vehicles in the second lane.

- *Does the service decrease the number of scenarios in which a long platoon of trucks, stuck just before the accident zone and waiting to dissolve and change lane, hinders or delays the arrival of emergency vehicles?*

  The service should lower the probability of an entire platoon arriving at the accident zone still in formation. This means, especially on a two-lane carriageway, that scenarios in which a high number of heavy vehicles delays the arrival of emergency vehicles to the accident zone could be reduced in number.

- *Does this cluster of use cases lower the chances of rear-end collision with slow or stationary vehicle?*

  The rear-end collision scenario is especially likely when the broke down vehicle or the accident zone is hidden by a turn or the visibility is hindered somehow. The actual impact of this cluster of use cases on safety should be evaluated keeping in mind that the leading vehicle should be generally equipped at least with the Forward Collision Warning and the Emergency Brake Assist systems, potentially able to prevent rear-end collision between the leading vehicle and the preceding one (or lower its severity).

Assessment instrument

To assess the jointed impacts, both field tests and modeling works can be employed. Field tests should focus in assessing safety-related parameters bound to human behavior while the modeling works should obtain values for the safety-related output like TTC and BTN, as function of the different human behavioral models and implementation scenarios. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. If the OEMs design the HMI to show only some of these information, which ones are displayed and when must be specified. Examples of this kind of specifications can be found in the dedicated C-Roads documents.

4.3.1.3 Environment

Research Question: Does the information granted by the service promote a more efficient driving both from platooned trucks and human-driven vehicles interacting with the platoons?

An earlier notification (or a more intrusive and detailed one) lead to an increased number of platoons able to pass the hazardous location without dissolving themselves. As confirmed by the literature review, increasing the number of kilometers driven in platoon formation leads to major fuel savings and lower emission levels. Besides, keeping the platoon together before and after the bottleneck section allows the CACC to perform its shockwave damping feature and foster an earlier return to the decongested state. Moreover, an increased situation awareness can ease the lane changing maneuver performed by the platoon and reduce its negative effects on the surrounding traffic flow, the number of sudden braking maneuvers can be reduced too. For the slow vehicle ahead warning the overtaking maneuver can be more efficient.

- *Does the service avoid the platoon dissolution?*

  Knowing about a slow vehicle ahead or an accident zone should make the lane change maneuver easier, avoiding the scenario in which the platoon finds itself stuck behind a broken down vehicle or an accident and must dissolve to surpass it, one truck at a time. As mentioned in the paragraphs above and in chapter 2, the disaggregation has negative impacts on fuel savings deriving from Truck Platooning. Moreover, not dissolving the platoon implies just one lane change maneuver needed, while separating the trucks means that each one of them must change lane, impacting the surrounding traffic flow. Accident zones and slow or stationary vehicles can easily impact on the traffic flow, temporarily worsening the capacity of the road. If the C-ITS service fosters the regularity of the truck platoon driving, the platoon in turn can absorb the shockwave propagating upstream, delaying or avoiding congestion and reducing the overall level of emissions.

- *Do the smoother lane changes have an impact on the surrounding traffic flow and on shockwaves creation and propagation?*

  The need to change lane for two or more heavy vehicles together can have negative impacts on surrounding road users, possibly imposing more abrupt braking due to the increased spaces needed for the platoon to change lane as a whole. Performing the maneuver in advance, not in close proximity to the bottleneck section and when the traffic is less congested, means wider gaps and smoother maneuvers. Lowering both the number and the severity of the shockwaves propagated upstream implies a more fuel-efficient driving and less accelerations and decelerations along the traffic flow.

- *How do the instant speed fluctuations change?*

  The leading vehicle's driver that knows about the dangerous event ahead starts decelerating earlier and doesn't have to brake suddenly. Also, having the platoon on the right lane when approaching the hazardous location implies a more regular driving and, therefore, lower emission levels.

- *Does the average speed decrease?*

  The increased awareness about a potentially hazardous event leads to lower speeds on the road. Fuel savings resulting from driving as part of a platoon are maximized for a certain speed value, probably higher than the one cautiously adopted by the leading vehicle's driver in this scenario.

- *Does the service decrease the number of scenarios in which a truck platoon suddenly finds itself stuck behind a slow or stationary vehicle or an accident zone?*

  In non-congested scenarios, a truck platoon can be forced to overtake starting from low speed values which means that, after braking, two or more heavy vehicles must strongly accelerate. If that is the case, fuel consumption is expected to rise.

Assessment instrument

Assess the environmental impacts on the traffic flow, especially in field tests where few platoons are employed, can be extremely challenging. As general rule, during a field test similar platoon features (headway, speed values) should be kept for each passage across the hazardous location to get comparable results. Field tests could be designed to obtain both the fuel-related benefits for the single platoon, deriving from the C-ITS service, and behavioral inputs that a model can employ to assess fuel consumption and, then, environmental impacts. The baseline scenarios considerable are the one in which a platoon doesn't receive the Use Case information and the one in which the same number of trucks passes through the hazardous location by themselves.

4.3.1.4 User Acceptance

Research Question 1: Does having the information earlier improve the situation awareness among the drivers, easing the lane changing task and improving the feeling of safety and system reliability?

Driving with a reduced headway can hinder the field of view for the following vehicles. Despite many solutions consider the view of the camera on the leading vehicle to be broadcasted to the following vehicles, in a long platoon the following vehicle driver could feel threatened during a lane changing maneuver (especially when abrupt or carried out with small gaps on the other lane). A smoother lane changing maneuver can improve the feeling of safety, while information about the situation ahead, broadcasted by the C-ITS service, can lead to an improved situation awareness. Besides, avoiding the platoon dissolution by the means of the C-ITS service can reduce the number of episodes in which the trucks find themselves to be stuck on the right lane, just before the bottleneck section, and unable to change lane. In this kind of scenario, the trucks ahead will travel earlier the accident zone (or surpass earlier the broken-down vehicle) while the following vehicle drivers could feel themselves left behind (a mainly critical scenario when the multi-brand platoons are considered).

Assessment instrument

To assess User Acceptance, the most efficient tools are Surveys presented after field tests and large-scale demonstrations.

Research Question 2: Do the drivers of the following vehicles feel safer with an increased situational awareness about dangerous locations? Do they understand more clearly the leading vehicle driver actions?

Knowing about dangerous locations can help the drivers of the following vehicles to understand why the driver of the leading vehicle is decelerating, for example. Also, knowing about an accident zone or another dangerous location should make the drivers feel safer and improve their user acceptance both towards Truck Platooning and C-ITS services. Besides, the take-over maneuver, if required, is carried out in a more conscious way and is not perceived as dangerous or improvised.

Assessment instrument

To assess User Acceptance, the most efficient tools are Surveys presented after field tests and large-scale demonstrations. It is important that the broadcasted message is displayed inside each vehicle, to let the following vehicle drivers know why the platoon is slowing down for example.

Research Question 3: Is the message delivered by the service clearly displayed on the platoon HMI? Is it clear how both the platoon and the single driver should behave?

It is important that the message designed for a generic vehicle equipped for the message reception doesn't turn out to be confusing for a driver possibly not in the driving loop, with reduced field of view and travelling in a platoon. It should be clear if he must do something or if only the platoon leader should drive accordingly.

Assessment instrument

To assess User Acceptance, the most efficient tools are Surveys presented after field tests and large-scale demonstrations. It is important that the broadcasted message doesn't result confusing on a platoon-dedicated HMI and that every driver understands who, inside the platoon, must react. If the OEMs design the HMI to show only some of these information, which ones are displayed and when must be specified.

4.3.2 Cluster 2: Traffic Jam Ahead

The drivers know about a traffic jam ahead their route thanks to the information sent by the road operator. The position, the length of the traffic jam and the section/lanes concerned are broadcasted, if the information is available. The promptness and precision of the message should be higher than conventional means, which means that preventive maneuvers can be accomplished in a smoother and more efficient way. Moreover, informing about the end of a queue allows the approaching drivers to adapt their speed and have an improved situational awareness, increasing Safety. Both Traffic Efficiency, Environment and Safety benefits are expected to be achieved through the Traffic Jam Ahead use case.

4.3.2.1 Traffic Efficiency

Research Question: Does the platoon drivers adapt their behavior because of the warnings/information given by the service?

Knowing about the position of the queue could impact on the driving behavior of driver of the leading vehicle and result in lower speed values and lane change maneuvers. Thus, two main impacts on traffic efficiency could be obtained, delaying the stop of the truck platoon would prolong the beneficial effect of the CACC on the traffic flow and signalizing the interested lane could make the lane changing maneuver smoother, possibly preventing the platoon from being stuck behind the queue.

- *Is the driver's speed (more) compliant with the suggested speed limit?*

  Receiving the suggested speed limit could have an impact on the behavior of the driver of the leading vehicle and, therefore, on the kept speed value. Also, having this suggested speed limit updated as soon as the downstream traffic conditions change means a readier adaptation when compared to the punctual information granted by the Variable Message Signs, for example. Both those effects should prevent the platoon from finding itself stuck in the congested traffic and exploit the CACC-related benefits mentioned above (or at least this moment should be delayed, prolonging the benefits on the traffic flow stability).

- *How does the lane change point vary? Is the lane change maneuver carried out in a smoother way?*

  Knowing about the queue ahead and the slowed down lanes can promote an earlier lane change maneuver, carried out as soon as a sufficient gap arises. If that is the case, no hard braking should occur in the vehicles on the other lane and lesser or smaller shockwaves should be generated. The lane changing maneuver is relevant especially when the traffic jam is located near an off-ramp, hindering only the first lane (and when that location is delivered to the truck platoon).

- *Does the platoon average speed decreases?*

  Knowing about a queue ahead and its length could promote a slower driving in the platoon. If that is the case, the platoon drives in formation and with acceptable speed for a longer time and the CACC dampening feature lasts longer.

- *Does the service avoid the platoon from getting stuck behind the queue?*

  If the lane occupied by the queue is signalized in advance, the probability for the platoon to be on the other lanes when approaching the section is higher. If a platoon formed by heavy vehicles doesn't get stuck behind a queue the situation of the queue itself doesn't worsen in length, on the other hand not having the platoon behind the queue means that there are no benefits from the CACC on the congested lane.

Assessment instrument

To assess the jointed impacts, both field tests (to evaluate the drivers' behavior) and modeling works can be employed. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. Examples of this kind of specifications can be found in the dedicated C-Roads documents [110]. Baseline scenarios could be the one in which no information is forwarded, the one in which the same information is given through VMS and the one in which the same information is forwarded to single trucks. The latter case should account both for trucks equipped and not equipped for the reception of the message.

4.3.2.2 Safety

Research Question: Does the information forwarded earlier and/or in a more continuous way promotes a smoother and safer driving for the platoon?

Although it is true that the Truck Platooning system should be able to prevent rear-end collision among the vehicles in formation, as seen in Chapter 2, it should be noted that heavy vehicles typically have lower deceleration capacities compared to the light vehicles. With strongly reduced headways then, collisions between the trucks could occur if the leading vehicle suddenly rear-ends with the vehicle ahead. The collision scenario becomes more likely when approaching a queue, if the leading vehicle's driver knows about the situation ahead, an improved situational awareness can prevent such accidents. Moreover, a smoother brake action of the leading vehicle becomes a smoother brake action in the last one in the platoon, lowering the risk of rear-end collisions from behind.

- *Does this cluster of use cases lower the chances of rear-end collision with the end of a queue?*

  The rear-end collision scenario is especially likely when the queue is hidden by a turn or the visibility is hindered somehow. The actual impact of this cluster of use cases on safety should be evaluated keeping in mind that the leading vehicle should be generally equipped at least with the Forward Collision Warning and the Emergency Brake Assist systems, potentially able to prevent rear-end collision between the leading vehicle and the preceding one (or lower its severity).

- *How do the instant speed fluctuations change?*

  The leading vehicle's driver that knows about the queue ahead starts decelerating earlier, in a more conscious way. This, in turn, should lead to smoother braking in the last vehicle of the platoon and, therefore, lower risk of rear-end collision from behind

- *Is the lane change maneuver smoother?*

  When the message content is precise enough, the leading vehicle's driver knows about the need to perform a lane change maneuver in advance which means that the possibility to find sufficient gaps increases. A wide gap should imply greater values for TTC and BTN and, therefore, less safety-critical scenarios during the maneuver.

Assessment instrument

To assess the jointed impacts mainly field tests can be employed, modeling works can evaluate the safety-related parameters obtained during a lane change maneuver carried out in order to avoid a queue. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. If the OEMs design the HMI to show only some of these information, which ones are displayed and when must be specified. Examples of this kind of specifications can be found in the dedicated C-Roads documents, baseline scenarios should refer mainly to platoons not equipped to get the C-ITS message. The redundancy with the Forward Collision Warning and the Emergency Brake Assist should be evaluated considering that the use case takes into account also V2V communication, potentially a platoon "being one *or two* vehicles behind the ones braking at the end of a traffic jam area" can receive the V2V message and start decelerating as soon as the braking vehicle does. This situation seems to fall out of the Forward Collision Warning and the Emergency Brake Assist domain and should be evaluated when defining additional impacts on safety.

4.3.2.3 Environment

Research Question: Does the information forwarded earlier and/or in a more continuous way promote a smoother driving, with fewer accelerations and decelerations and consequently lower emission levels? Does the information prevent the truck platooning from being stuck in the congested traffic?

An earlier notification leads to an increased number of platoons able to avoid being stuck behind the queue and the suggested speed limit should increase the time spent in formation before reaching the queue. As confirmed by the literature review, increasing the time driven in platoon formation leads to major fuel savings, lower emission levels and CACC dampening effects. Also, an increased situation awareness can ease the lane changing maneuver performed by the platoon and reduce its negative effects on the surrounding traffic flow, the number of sudden braking maneuvers can be reduced too.

- *Do the smoother lane changes have an impact on the surrounding traffic flow and on the creation and propagation of the shockwaves? (Relevant when the lane occupied by the queue is identified and broadcasted)*

  The need to change lane for two or more heavy vehicles together can have negative impacts on surrounding road users, possibly imposing more abrupt braking due to the increased spaces needed for the platoon to change lane as a whole. Performing the maneuver in advance, not in close proximity to the end of the queue and when the traffic is less congested, means wider gaps and smoother maneuvers. Lowering both the number and the severity of the shockwaves propagated upstream leads to a more fuel-efficient driving and less accelerations and decelerations along the traffic flow.

- *How do the instant speed fluctuations change?*

  The leading vehicle's driver that knows about the queue ahead starts decelerating earlier and doesn't have to brake suddenly.

- *How does the presence of truck platoons upstream the hazardous location impact on traffic flow?*

  Queues and Traffic Jams can easily impact on the traffic flow, temporarily worsening the capacity of the road. If the C-ITS service fosters the regularity of the truck platoon driving, the platoon in turn can absorb the shockwave propagating upstream, delaying or avoiding congestion.

- *Do the informed platoons actually avoid getting stuck in traffic jams? If not, does the informed platoons reach later the congested sections (therefore being stuck for lower time)?*

  Until the platoon's speed doesn't drop below 50 km/h [106], aerodynamic benefits are achieved and fuel consumption is reduced. This means that delaying or avoiding reaching the traffic jam or the queue by the means of a reduced speed value can potentially result in lower emissions generated from the platoon.

Assessment instrument

To assess the environmental impacts, especially in field tests where few platoons are employed, can be extremely challenging. It should be possible to evaluate the fuel savings for the single platoon, though. To evaluate broader impacts on the whole traffic flow modeling works should be considered, instead. The baseline scenarios considerable are the one in which a platoon doesn't receive the Use Case information at all and the one in which the information is granted by the means of Variable Message Signs. Besides, different scenarios including different levels of market penetration could be considered in the modeling works.

4.3.2.4 User Acceptance

Research Question 1: Does having the information earlier improve the situation awareness among the drivers, easing the lane changing task and improving the feeling of safety and system reliability?

Driving with reduced headways can hinder the field of view for the following vehicles. Despite many solutions consider the view of the front camera of the leading vehicle to be broadcasted to the following vehicles, in a long platoon the following vehicle driver could feel threatened during a lane changing maneuver, especially when abrupt or carried out with small gaps on the other lane. A smoother lane changing maneuver can improve the feeling of safety, while information about the situation ahead, broadcasted by the C-ITS service, lead to an improved situation awareness.

Research Question 2: Is the message delivered by the service clearly displayed on the platoon HMI? Is it clear how both the platoon and the single driver should behave?

It is important that the message designed for a generic vehicle, equipped for the message reception, doesn't turn out to be confusing for a driver possibly not in the driving loop, with reduced field of view and travelling in a platoon. It should be clear if he must do something or if only the platoon leader should drive accordingly. If the OEMs design the HMI to show only some of these information, which ones are displayed and when must be specified.

Assessment instrument

To assess User Acceptance, the most efficient tools are Surveys presented after field tests and large-scale demonstrations.

4.3.3 Cluster 3: Weather Condition Warning – Temporarily slippery road

Both the use cases included in this cluster concern situations where the adhesion of the road surface and/or the visibility are compromised. The first use case allows the drivers to know about accurate and up-to-date local weather information thanks to the information sent by the road operator or another service provider. Exceptional weather conditions (defined by the Commission Delegated Regulation (EU) 886/2013 as unusual, severe or unseasonal weather conditions) are signaled, especially where the danger is difficult to perceive visually, such as black ice or strong gusts of wind. Temporary slippery road faces situations in which a road operator knows that a section of a road (or a single lane or point) is temporarily slippery and broadcasts the information. The expected impacts are an increased driver attention, an adaptation of the travelling speed and possible rerouting. Therefore, the main benefits are safety-related, enhancement also in Traffic Efficiency, Environment and User Acceptance can be expected, though.

4.3.3.1 Traffic Efficiency

Research Question: How does the driving changes for a platoon of trucks?

Knowing in advance about adverse weather conditions and reduced road adhesion can warn the platoon system or the truck drivers. Depending mainly on the robustness of the CACC algorithm, the braking capacity of each truck and the planned headway values, the platoon can face the issues arising from a reduced road adhesion both dissolving in advance or increasing the headway value (to make the single truck able to brake before colliding with the preceding one). If the visibility is reduced to a point where the on-board sensors are no longer able to perceive the surrounding environment, the platoon must dissolve, instead. Dissolution should happen also if the signal coverage is compromised beyond a certain value. In every scenario, an earlier adaptation/dissolution means smoother maneuvers and decreased impacts on the surrounding traffic flow, though. For the slippery road warning, similar considerations can be made about the dissolution or the headway adaptation, in this case the smoothness of the lane change maneuver must be considered too (when the information includes the interested lanes).

On the basis of the bibliographical review, while evaluating the scenarios involving puddles of unidentified liquid on the road, the following assumptions are going to be made:

- If one of the lanes accessible to the platoon isn't affected by the spillage of various materials (or puddle generated by natural causes), the platoon tries to change lane and avoid said spillage.
- If the platoon can't avoid the interested lanes or the whole carriageway is involved, the platoon must dissolve, to avoid loss of adhesion for the wheels and potential rear-end collisions.

➢ *Does the information forwarded by the service allow the platoon to keep its formation, regardless of the adverse weather conditions?*

Knowing in advance about ice or water on the road can grant to the truck platoon sufficient spaces to adapt the kept headway and avoiding possible dissolutions due to safety-related reasons and lacking acceleration/adhesion capacities of the following vehicles. Avoiding the dissolution means reduced impacts on the surrounding traffic flow but increasing the headway can involve unwanted cut-ins from external vehicles (as mentioned in Chapter 2 or in the paragraph 3.1).

➢ *Does the information forwarded by the service allow smoother disaggregation maneuvers?*

Knowing in advance when the disaggregation maneuver is needed allow the platoon to perform the disaggregation maneuver in a smoother way because the trucks can decelerate accordingly without adhesion issues and there is no urgency to accomplish the disaggregation. Avoiding harsh braking and reducing the time needed for the maneuver to be carried out should lessen the impact on the vehicles behind the platoon, as explained in chapter 2 and in the paragraph 3.1). Besides, on the basis of the instructions received by the drivers, the platoon could have to dissolve mandatorily before a spillage or a puddle (in this case it could be forced to stop just before the compromised section) or as soon as this section is passed. Having the information forwarded in advance should avoid such scenarios and foster smoother and shorter disaggregation maneuvers (compromised adhesion means decreased feasible deceleration values).

➢ *Does the average speed decreases?*

Even though, in adverse weather conditions the traffic flow as a whole slows down, there could be scenarios in which a truck platoon informed by the service slows down more than the rest of the surrounding traffic and becomes a moving bottleneck.

- *Does the information forwarded by the service allow the platoon to keep its formation, avoiding the spillage by changing lane in advance?*

  Knowing about the presence and the position of the spillage on the road ahead, the platoon leader knows if there are clean lanes and can start earlier searching for a gap for the lane change maneuver. If the information is not received, the platoon can find itself forced to pass through the spillage and, then, dissolve because normal braking spaces could be unforeseeably incremented by the liquid on the wheels.

- *Does the information forwarded by the service avoid sudden braking by the platoon? Does it avoid scenarios in which the platoon completely stops before the compromised section?*

  Being surprised by the sudden appearance of a spillage or a natural puddle on the road can lead the leader vehicle's driver to brake considerably, possibly impacting the traffic flow upstream. Also, depending on the guidelines provided to the drivers, the platoon could stop just before the compromised section and dissolve before passing over the spillage or the puddle (one truck at a time). This kind of maneuver is the less efficient and certainly impacts on the surrounding traffic flow.

Assessment instrument

To assess the jointed impacts, both field tests (to evaluate the drivers' behavior and system robustness when facing adverse weather conditions) and modeling works can be employed. During the field test design, for each weather scenario considered a driving procedure should be defined for the drivers to avoid confusion and indecision about how behave while driving in a platoon and facing an adverse weather condition. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted, the coverage of the service during adverse weather condition should be assessed. Examples of this kind of specifications can be found in the dedicated C-Roads documents [110]. Also, each use case included in the cluster should be evaluated separately.

4.3.3.2 Safety

Research Question: Does the information forwarded in advance allow the platoon to adapt its driving to face the adverse weather conditions or decreased adhesion of the road ahead? Does it grant an improved situational awareness in the drivers?

Both reduced adhesion and hindered visibility lead to an increased headway between the trucks or to the platoon dissolution. Whatever the maneuver adopted by the platoon, decelerations are involved which means that knowing in advance of the situation ahead should anticipate those decelerations while the road adhesion is still granted. Also, an improved situational awareness lead to smoother maneuvers and hinders sudden and improvised responses by the truck drivers (that, when visibility and adhesion are hindered, could lead to safety-critical scenarios).

- *Does the platoon dissolve or adapt its headway before reaching the adverse weather area?*

  Having the information forwarded in advance should allow the platoon to reach the critical area with an increased headway or already dissolved, avoiding safety-critical scenarios and imposed deceleration maneuvers carried out when road adhesion is hindered.

- *Is the disaggregation maneuver carried out in a smoother and safer way?*

  Performing the disaggregation before reaching the adverse weather condition or the spillage on the road means that no urgency subsists and, therefore, no sudden or abrupt braking should be undertaken by the drivers.

- *Does an improved situational awareness help the drivers identify dangers difficult to perceive visually, such as black ice or strong gusts of wind?*

  Weather related dangers or liquids on the road can be difficult to perceive visually, especially for a following vehicle's driver that has a reduced field of view (as mentioned in Chapter 2). This means that if those drivers are warned about the situation, they can adapt their headway accordingly. Also, an improved situational awareness could hasten the take-over action performed by the driver for higher levels of automation (like the L3 one).

- *Does the information provided by the service help the platooning algorithm or the drivers chose when dissolve the platoon, also considering the road grade?*

  As mentioned in Chapter 2, the platooning system must take into account also the road grade while imposing the headway value. Having the information about a reduced adhesion value due to, for example, ice, would improve the algorithm precision and lower the number of disaggregation maneuvers imposed by the adverse weather conditions (that could be faced adapting the headway, instead). It should be highlighted that the information about road grade is not given by this service, though, but could be obtained by the means of the cameras equipped on board and able to record road signals if the visibility is not hindered by the weather conditions.

- *Is the lane change maneuver smoother?*

  When the message content is precise enough, the leading vehicle's driver knows in advance about the need to perform a lane change maneuver to avoid spillages or puddles ahead which means that the possibility to find sufficient gaps increases. A wide gap should imply greater values for TTC and BTN and, therefore, less safety-critical scenarios during the maneuver.

- *Does the average speed decrease?*

  The increased awareness leads to lower speeds on the road and, potentially, to reduced sudden and relevant braking when the event is reached.

- *Does the forwarded information lower the number of scenarios in which the platoon completely stops before the compromised section?*

  Being surprised by the sudden appearance of a spillage or a natural puddle on the road can lead the leader vehicle's driver to brake considerably. Also, depending on the guidelines provided to the drivers, the platoon could stop just before the compromised section and dissolve before passing over the spillage or the puddle (one truck at a time). This kind of maneuver could tempt vehicles stuck behind the platoon overtaking or changing lane in a sudden way.

Assessment instrument

To assess the jointed impacts mainly field tests can be employed, modeling works can evaluate the safety-related parameters obtained during a lane change maneuver carried out in order to avoid a spillage or a natural puddle. During the field test design, for each weather scenario considered a driving procedure should be defined for the drivers to avoid confusion and indecision about how behave while driving in a platoon and facing an adverse weather condition. Also, a careful tuning of the headway assumed by the platoon in the various situation should be conducted on the basis of the mechanical features of the employed trucks, the expected weathers condition and the available bibliography. Also the robustness of the system when facing packet losses and transmission delays should be evaluated before the field test. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. Examples of this kind of specifications can be found in the dedicated C-Roads documents, baseline scenarios should refer mainly to platoons not equipped to get the C-ITS message.

4.3.3.3 Environment

Research Question 1: Does the information forwarded by the service allow the platoon to keep its formation, regardless of the adverse weather conditions or liquids on the road?

As mentioned in 4.3.3.1 and in 4.3.3.2, the information forwarded in advance can lower the number of disaggregation maneuvers imposed to the platoon by external events. An increased number of kilometers travelled in formation implies fuel savings and environmental benefits as extensively explained in Chapter 2.

- *Does the information allow the rerouting of platoons on itineraries that can be travelled in formation for a greater number of kilometers (and, therefore, more fuel efficient)?*

  The use case Temporarily slippery road explicitly mentions the rerouting function, but weather condition warning could be considered too by optimization models like the one observed in 2.4. The information can, therefore, be employed by a service provider to reroute the fleet vehicles but also by the single platoons, if the drivers can agree on an alternative path and the message is received sufficiently in advance.

Research Question 2: Does the platoon driving impact less on the surrounding traffic flow?

An increased situation awareness can ease the lane changing maneuver performed by the platoon to pass through a section hindered by liquids on one or more lanes and reduce its negative effects on the surrounding traffic flow. Also, the headway adaptation or the disaggregation maneuvers carried out by the platoon in response of the considered events should be smoother and the number of sudden braking maneuvers can be reduced too, reducing the impact of these maneuver on the surrounding traffic flow and the creation and propagation of shockwaves upstream.

Assessment instrument

To assess the platoon fuel savings can be extremely challenging due to the randomness of the environmental parameters characterizing adverse weather conditions. It should still be possible to evaluate the fuel consumption for the single platoon related to the single event, though, especially on track tests rather than tests carried out on public roads (as mentioned in 2.4). To evaluate broader impacts on the whole traffic flow, instead, modeling works should be considered. The baseline scenarios considerable are the one in which a platoon doesn't receive the Use Case information at all and the one in which the information is granted by the means of Variable Message Signs.

4.3.3.4 User Acceptance

Research Question 1: Does having the information earlier improve the situation awareness among the drivers, easing the driving task and improving the feeling of safety and system reliability?

Driving with reduced headway can hinder the field of view for the following vehicles. Despite many solutions consider the view of the front vehicle camera to be broadcasted to the following vehicles, approaching an adverse weather condition area can surprise drivers and make them feel suddenly threatened by the reduced headway. Having consciousness of the weather conditions ahead and knowing that the system is aware of that too should help drivers trust the automation in threatening scenarios like the weather-related ones. Also, being informed of liquids on the road and reaching this section with the platoon already dissolved or positioned on clean lanes should lessen the impact of these scenarios on the drivers' feeling of safety and system reliability.

Research Question 2: Is the message delivered by the service clearly displayed on the platoon HMI? Is it clear how both the platoon and the single driver should behave?

It is important that the message designed for a generic vehicle, equipped for the message reception, doesn't turn out to be confusing for a driver possibly not in the driving loop, with reduced field of view and travelling in a platoon. It should be clear if he must do something or if only the platoon leader should drive accordingly. Besides, a clear display of the C-ITS message should prevent drivers to leave the platoon on their own initiative in response to adverse weather conditions.

Assessment instrument

To assess User Acceptance, the most efficient tools are Surveys presented after field tests and large-scale demonstrations.

5 Appendix

A.1. Truck Platooning impact evaluation

A.1.1. Traffic Efficiency

Data requirements – route parameters – design choices

The following parameters/data should be collected from equipped trucks or implemented in a simulation model:

- Leading and Following vehicles Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration of the platooning vehicles – source: Can Bus data or GPS data
- Delay/Time between the start of the merging maneuver and the platoon formation – source: CAN Bus data or GPS data
- Position – source: GPS data
- Steering angle – source: Can Bus data
- Other lane Average Speed – source: on-road detectors
- Average Gap – source: only through modeling works
- Traffic density – source: on-road detectors
- Headway or Spacing Policy – source: OEMs choice
- Maximum deceleration achievable by each truck – source: Can Bus data
- Number of vehicles in the platoon or the Platoon length
- Number of heavy vehicles queued behind the platoon
- Acceleration lane length – source: known physical feature of the infrastructure
- Steering angle of the vehicle entering or exiting through a ramp – source: only through modeling
- Speed of the vehicle entering or exiting through a ramp
- Length of the deceleration lane – source: known physical feature of the infrastructure
- Transmission delays – source: Can Bus

Field Test Indicators – Modeling Outputs

The following parameters should be collected or recorded as model outputs:

- Leading and Following vehicles Average Speed during the merging maneuver – source: Can Bus data or GPS data
- Platooning vehicles Speed standard deviation – source: Can Bus data or GPS data

- Platooning vehicles instantaneous accelerations and decelerations – source: Can Bus data
- Number of vehicles between the two platooning trucks (number of heavy vehicles between the two trucks should be considered) – source: GPS data or cameras data
- Time needed for the merging to be completed – source: Can Bus data or GPS data
- Number of interrupted merging or disaggregation maneuvers – source: Can Bus data or GPS data
- Time needed to dissolve the platoon – source: Can Bus data or GPS data
- Lane change point – source: Can Bus data or GPS data
- Lane change point for the vehicles behind the platoon – source: only through modeling works
- Number of vehicles that change lane behind the platoon – source: only through modeling works
- Number of overtaking vehicles that re-enter the first lane ahead one of the trucks – source: Cameras or through modeling works
- Number of vehicles forced (by the platoon) to stop on the acceleration lane and number of vehicles that keep driving on the hard shoulder – source: on-road cameras
- Instantaneous accelerations and decelerations of the vehicles willing to exit or enter through a ramp – source: only through modeling
- Maximum steering angle of the vehicles willing to exit or enter through a ramp – source: only through modeling
- Number of vehicles unable to take the off-ramp on time – source: through modeling or through on-road cameras
- Traffic densities below which the formation of the platoon can be maintained – source: only through modeling
- Time Gap Accuracy/Stability or Error in Spacing – source: Radar and GPS or Can Bus Data

Overall future estimated impact KPI (when penetration rate will be higher)

The following Key Performance Indicators (based on EIP list) can be estimated starting from the outputs of field test data or simulation works.

- Change in Traffic Flow
- Change in Journey Time
- Change in Total Time spent by all vehicles in queue

Overview of the research questions

Traffic Efficiency - Data Requirements	How does the merging maneuver impact on the traffic flow? How does the traffic flow impacts on the merging maneuver?	How does the disaggregation maneuver impact on the traffic flow?	How do the on-ramp interactions impact on traffic flow?	How do the off-ramp interactions impact on traffic flow?	How much can the CACC-equipped platoons delay traffic jam creation? How much earlier is the congestion absorbed thanks to this?
Speed	X	X	X	X	X
Acceleration Deceleration	X	X	X	X	X
Maximum deceleration achievable by each truck		X			
Delay/Time needed for the maneuver	X				
Position	X	X	X	X	X
Other lane average speed	X	X			
Other lane average gap	X	X			
Headway or Spacing Policy	X	X	X	X	X

Traffic Efficiency - Data Requirements	How does the merging maneuver impact on the traffic flow? How does the traffic flow impacts on the merging maneuver?	How does the disaggregation maneuver impact on the traffic flow?	How do the on-ramp interactions impact on traffic flow?	How do the off-ramp interactions impact on traffic flow?	How much can the CACC-equipped platoons delay traffic jam creation? How much earlier is the congestion absorbed thanks to this?
Number of heavy vehicles queued behind the platoon			X		
Number of vehicles in the platoon		X	X	X	
Steering angle			X	X	
Transmission delays					X
Length of the acceleration lane			X		
Length of the deceleration lane				X	
Traffic density	X		X	X	X

Traffic Efficiency - Field Test Indicators and Modeling Outputs	How the merging maneuver impacts on the traffic flow? How does the traffic flow impacts on the merging maneuver?	How the disaggregation maneuver impacts on the traffic flow?	How the on-ramp interactions impact on traffic flow?	How the off-ramp interactions impact on traffic flow?	How much the CACC-equipped platoons can delay traffic jam creation? How much earlier the congestion is absorbed thanks to this?
Average Speed	X	X	X	X	X

Traffic Efficiency - Field Test Indicators and Modeling Outputs	How the merging maneuver impacts on the traffic flow? How does the traffic flow impacts on the merging maneuver?	How the disaggregation maneuver impacts on the traffic flow?	How the on-ramp interactions impact on traffic flow?	How the off-ramp interactions impact on traffic flow?	How much the CACC-equipped platoons can delay traffic jam creation? How much earlier the congestion is absorbed thanks to this?
Speed Standard Deviation	X	X	X	X	X
Instantaneous Acceleration/Deceleration	X	X	X	X	X
Number of vehicles between the two platooning trucks	X				
Delay/Time needed for the maneuver to be completed	X	X			
Number of interrupted maneuvers	X	X			
Lane change point		X	X	X	
Number of lane changes		X			
Number of overtaking maneuvers		X			
Time Gap Accuracy/Stability					X
Number of stops on the acceleration lane/number of vehicles that can't take the off ramp			X	X	

Traffic Efficiency - Field Test Indicators and Modeling Outputs	How the merging maneuver impacts on the traffic flow? How does the traffic flow impacts on the merging maneuver?	How the disaggregation maneuver impacts on the traffic flow?	How the on-ramp interactions impact on traffic flow?	How the off-ramp interactions impact on traffic flow?	How much the CACC-equipped platoons can delay traffic jam creation? How much earlier the congestion is absorbed thanks to this?
Number of vehicles that drives on the hard shoulder			x		
Maximum steering angle			x		
Traffic densities below which the formation can be maintained			x	x	

A.1.2. Safety

Data requirements – route parameters – design choices

The following parameters/data should be collected from equipped trucks or implemented in a simulation model:

- Platooning Vehicles Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration or Brake pressure profile – source: Can Bus data or GPS data
- Position – source: GPS data
- Headway or Spacing Policy – OEMs choice
- Transmission delays – source: Can Bus data
- Time To Collision (TTC) – source: Sensors data
- Brake Threat Number (BTN) – source: Sensors data
- Position – source: GPS data
- Tunnel length – source: known physical feature of the infrastructure
- Axles alignment standard deviation – source: Cameras
- Gross weight per axle – source: Can Bus data

Field Test Indicators – Modeling Outputs

The following parameters should be collected or recorded as model outputs:

- Vehicles Average Speed and Speed standard deviation during analyzed maneuvers – source: Can Bus data or GPS data
- Vehicles instantaneous accelerations and decelerations during analyzed maneuvers – source: Can Bus data
- Maximum accelerations and decelerations during analyzed maneuvers – source: Can Bus data
- Lane change point – source: Can Bus data or GPS data
- Minimum TTC and Minimum BTN/ Number of events involving safety-critical values of BTN and TTC – source: Sensors data
- Number of Cut-ins/Km for each headway value considered – source: Cameras or Sensors data
- Maximum steering angle – source: Can Bus data
- Time Gap Accuracy/Stability or Error in Spacing – source: Radar and GPS
- Time needed for a queue to dissolve – Only through modeling
- Travel time delay/Time the platoon gets stuck behind a queue – source: GPS data

Overall future estimated impact KPI (when penetration rate will be higher)

The following Key Performance Indicators (based on EIP list) when the automation level will be L4 or higher can be estimated starting from the outputs of the field test data:

- Change in number of accidents, fatalities and injuries
- Change in number of involved drivers

Overview of the research questions

Safety - Data Requirements	Can the maneuvers performed by the platoon-equipped trucks and their interaction with other road users lead to dangerous scenarios?	There are points, along the route, that could be potentially dangerous when travelled by a truck platoon or inadequate for its transit?
Speed	**X**	**X**
Acceleration Deceleration or Brake Pressure profile	**X**	**X**

Safety - Data Requirements	Can the maneuvers performed by the platoon-equipped trucks and their interaction with other road users lead to dangerous scenarios?	There are points, along the route, that could be potentially dangerous when travelled by a truck platoon or inadequate for its transit?
Position	X	X
Time To Collision (TTC)	X	X
Brake Threat Number (BTN)	X	X
Headway or Spacing Policy	X	X
Transmission delays	X	X
Tunnel length		X
Axles alignment standard deviation		X
Gross weight per axle		X
Time Gap Accuracy/Stability		X
Traffic density	X	

Safety - Field Test Indicators - Modeling Outputs	Can the maneuvers performed by the platoon-equipped trucks and their interaction with other road users can lead to dangerous scenarios?	There are points, along the route, that could be potentially dangerous when travelled by a truck platoon or inadequate for its transit?
Average Speed	X	X
Speed Standard Deviation	X	X
Instantaneous Accelerations/Decelerations	X	X
Maximum accelerations and decelerations	X	X
Minimum Time To Collision (TTC)	X	X
Minimum Brake Threat Number (BTN)	X	X
Lane change point	X	X
Number of Cut-ins/Km	X	X
Maximum steering angle	X	X

A.1.3. Environment

Data requirements – route parameters – design choices

The following parameters/data should be collected from equipped trucks or implemented in a simulation model:

- Platoon vehicles Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- Kilometres out of formation tied to each maneuver – source: GPS data or Can Bus data
- Headway or Spacing Policy – source: OEMs choice
- Number of vehicles in the platoon – Platoon length – Position along the platoon
- Gross weight per axle – source: Can Bus data
- Environmental features (e.g. Wind speed/direction, temperature, etc.) – source: weather stations
- Average fuel consumption per kilometer – source: Can Bus data
- Car following model – source: OEMs choice
- Traffic density – source: on-road detectors or through modeling works
- Road geometrical feature – source: known physical feature of the infrastructure

Field Test Indicators – Modeling outputs

The following parameters should be collected or recorded as model outputs:

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Number of imposed maneuvers per kilometer – source: Can Bus data or GPS data
- Number of Cut-ins/Km for each headway value considered – source: Cameras
- Number of kilometers out of formation – source: Can Bus data or GPS data
- Fuel consumption – source: Can Bus data
- Average flow across the bottleneck section – source: on-road detectors or modeling works
- Dynamic capacity (i.e., the downstream outflow from traffic congestion) – source: on-road detectors or modeling works

Overall future estimated impact KPI (when penetration rate will be higher)

The following Key Performance Indicators (based on EIP list) can be estimated starting from the outputs of field test data or simulation works.

- Change in Traffic Flow
- Change in Journey Time
- Change in Total Time spent by all vehicles in queue
- Change in Road Capacity
- Change in traffic CO_2 or polluting emissions
- Change in noise pollution
- Change in fuel consumption

Overview of the sub-research questions

Environment - Data Requirements	How does Truck Platooning impact on fuel consumption for the single truck? How does it impact on traffic flow stability and infrastructure efficiency?	How does a certain market penetration of Truck Platooning affect the traffic flow stability, improving the infrastructure efficiency and decreasing the number of accelerations and decelerations?
Speed	**X**	
Acceleration/Deceleration	**X**	**X**
Kilometers out of formation tied to each maneuver	**X**	
Number of vehicles in the platoon	**X**	
Position	**X**	
Headway or Spacing Policy	**X**	**X**

Environment - Data Requirements	How does Truck Platooning impact on fuel consumption for the single truck? How does it impact on traffic flow stability and infrastructure efficiency?	How does a certain market penetration of Truck Platooning affect the traffic flow stability, improving the infrastructure efficiency and decreasing the number of accelerations and decelerations?
Fuel consumption	**X**	**X**
Car Following Model		**X**
Road geometrical features		**X**
Traffic density		**X**

Environment - Field Tests Indicators and Modeling Outputs	How does Truck Platooning impact on fuel consumption for the single truck? How does it impact on traffic flow stability and infrastructure efficiency?
Average Speed	**X**
Instantaneous accelerations/decelerations	**X**
Speed Standard Deviation	**X**
Number of imposed maneuvers per kilometer	**X**
Number of cut-ins/Km for each headway value considered	**X**

Environment - Field Tests Indicators and Modeling Outputs	How does Truck Platooning impact on fuel consumption for the single truck? How does it impact on traffic flow stability and infrastructure efficiency?
Fuel consumption	x

A.1.4. Overall and User Acceptance

5.1.1.1 Field test Indicators and Survey's Outputs

The following indicators should be collected after surveys:

- Situation awareness
- Knowledge about the Truck Platooning system
- Perception of the Truck Platooning system and of the automation, in general
- Perception's problems related to each maneuver
- Perceived threats
- Trust in the automation
- Number of interrupted maneuvers

A.2. Jointed impacts of Truck Platooning and C-ITS

A.2.1. *Roadworks Warning - Closure of part of a lane, whole lane or several lanes*

Traffic Efficiency

Data requirements – route parameters – design choices

The following parameters/data should be collected from equipped trucks and communication sources or implemented in a simulation model:

- Message sent and received/Message content – Data logs
- Reception point / HMI display – Can Bus data and GPS data
- Platoon vehicles Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- Lateral lane deviation – source: Cameras
- Headway or Spacing Policy – source: OEMs choice
- Platooning vehicles steering angle – source: Can Bus

- Number of vehicles in the platoon – Platoon length – Position along the platoon

Field Test Indicators – Modeling outputs

The following parameters should be collected or recorded as model outputs:

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Lane change point – source: GPS data or Can Bus data
- Gap chosen for the lane changing maneuver – source: only through modeling or algorithm specifications
- Traffic densities beyond which the lane changing maneuver is hindered – source: on-road detectors or modeling works
- Average flow across the bottleneck section – source: on-road detectors or modeling works
- Dynamic capacity (i.e., the downstream outflow from traffic congestion) – source: on-road detectors or modeling works
- Disaggregation starting point – source: Can Bus data or GPS data

Overview of the sub-research questions

Traffic Efficiency - Data Requirements	Does the information allow the platoon to change lane earlier and to keep its formation? Does the lane change point vary?	Is the platoon lane changing maneuver smoother thanks to the received information?	The platoon dissolution is accomplished in a more efficient way?	Is the platoon speed more homogeneous?	Does an increased number of platoons passing through the work zone in formation enhance the traffic flow?
Message sent and received - Message content	**X**	**X**	**X**	**X**	
Reception point - HMI display	**X**	**X**	**X**	**X**	**X**
Speed			**X**	**X**	**X**

Traffic Efficiency - Data Requirements	Does the information allow the platoon to change lane earlier and to keep its formation? Does the lane change point vary?	Is the platoon lane changing maneuver smoother thanks to the received information?	The platoon dissolution is accomplished in a more efficient way?	Is the platoon speed more homogeneous?	Does an increased number of platoons passing through the work zone in formation enhance the traffic flow?
Acceleration - Deceleration			X	X	X
Position	X	X	X	X	X
Lateral lane deviation	X	X			
Headway or Spacing Policy			X		X
Steering angle	X	X	X		
Number of vehicles in the platoon/Platoon length	X	X	X		X

Traffic Efficiency - Field test indicators	Does the information allow the platoon to change lane earlier and to keep its formation? Does the lane change point vary?	Is the platoon lane changing maneuver smoother thanks to the received information?	The platoon dissolution is accomplished in a more efficient way?	Is the platoon speed more homogeneous?	Does an increased number of platoons passing through the work zone in formation enhance the traffic flow?
Average Speed			**X**	**X**	
Speed Standard Deviation			**X**	**X**	
Instantaneous acceleration and decelerations		**X**	**X**	**X**	**X**
Lane Change Point	**X**	**X**			
Gap chosen for the lane changing maneuver	**X**	**X**			
Traffic densities beyond which the lane changing maneuver is hindered	**X**				
Average flow across the bottleneck section					**X**
Dynamic capacity					**X**

Traffic Efficiency - Field test indicators	Does the information allow the platoon to change lane earlier and to keep its formation? Does the lane change point vary?	Is the platoon lane changing maneuver smoother thanks to the received information?	The platoon dissolution is accomplished in a more efficient way?	Is the platoon speed more homogeneous?	Does an increased number of platoons passing through the work zone in formation enhance the traffic flow?
Disaggregation starting point	x		x		

Safety

Data requirements – route parameters – design choices

The following parameters/data should be collected from equipped trucks and communication sources or implemented in a simulation model:

- Message sent and received/Message content – Data logs
- Reception point – Can Bus data and GPS data
- Platoon vehicles Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- Headway or Spacing Policy – source: OEMs choice
- Platooning vehicles steering angle – source: Can Bus data
- TTC and BTN – source: Sensors data
- Number of vehicles in the platoon – Platoon length – Position along the platoon

Field Test Indicators – Modeling outputs

The following parameters should be collected or recorded as model outputs:

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Lane change point – source: Can Bus data or GPS data
- Gap chosen for the lane changing maneuver – source: only through modeling or algorithm specifications
- Minimum TTC and Minimum BTN/ Number of events involving safety-critical values of BTN and TTC – source: Sensors data

- Disaggregation starting point – source: Can Bus data or GPS data
- Lateral Position Standard Deviation – source: Sensors data

Overview of the sub-research questions

Safety - Data Requirements	Is the platoon lane changing maneuver smoother thanks to the received information?	Is the platoon speed more homogeneous?	Does an L3 platoon disaggregates if the received information about the roadworks topology could hinder the lateral control (e.g. unsuitable lane markings, road cones etc.)?
Message sent and received/Message content	X	X	X
Reception point / HMI display	X	X	X
Speed		X	
Acceleration/Deceleration	X	X	
Position			X
TTC / BTN	X		
Headway or Spacing Policy			
Steering angle	X		

Safety - Data Requirements	Is the platoon lane changing maneuver smoother thanks to the received information?	Is the platoon speed more homogeneous?	Does an L3 platoon disaggregates if the received information about the roadworks topology could hinder the lateral control (e.g. unsuitable lane markings, road cones etc.)?
Number of vehicles in the platoon/Platoon length	X		X

Safety - Field test indicators	Is the platoon lane changing maneuver smoother thanks to the received information?	Is the platoon speed more homogeneous?	Does an L3 platoon disaggregates if the received information about the roadworks topology could hinder the lateral control?
Average Speed		X	
Speed Standard Deviation		X	
Instantaneous acceleration and decelerations	X	X	
Lane Change Point	X		
Gap chosen for the lane changing maneuver	X		
Minimum TTC and Minimum BTN / Number of events involving safety critical values of BTN and TTC	X		

Safety - Field test indicators	Is the platoon lane changing maneuver smoother thanks to the received information?	Is the platoon speed more homogeneous?	Does an L3 platoon disaggregates if the received information about the roadworks topology could hinder the lateral control?
Disaggregation starting point			X
Lateral Position Standard Deviation			X

Environment

Data requirements – route parameters – design choices

The following parameters/data should be collected from equipped trucks or implemented in a simulation model:

- Message sent and received/Message content – Data logs
- Reception point / HMI display – source: GPS data and Can Bus data
- Platoon vehicles Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- Kilometers out of formation – source: GPS data
- Headway or Spacing Policy – source: OEMs choice
- Number of vehicles in the platoon – Platoon length – Position along the platoon
- Platooning vehicles steering angle – source: Can Bus data
- Environmental features (e.g. Wind speed/direction, temperature, etc.) – source: weather stations
- Average fuel consumption per kilometer – source: Can Bus data

Field Test Indicators – Modeling outputs

The following parameters should be collected or recorded as model outputs:

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Lane change point – source: Can Bus data or GPS data

- Maximum steering angle – source: Can Bus data
- Number of platoons able to pass through the roadworks in formation – source: GPS data
- Gap chosen for the lane changing maneuver – source: only through modeling or algorithm specifications
- Traffic densities beyond which the lane changing maneuver is hindered – source: on-road detectors or through modeling works
- Average flow across the bottleneck section – source: on-road detectors or through modeling works
- Disaggregation starting point – source: Can Bus data and GPS data
- Fuel consumption – source: Can Bus data

Overview of the sub-research questions

Environment - Data Requirements Roadworks Warning	Does the service allow a greater number of platoons to keep their formation?	Do the smoother lane changes have an impact on the surrounding traffic flow and on shockwaves creation and propagation?	Does the CACC system promote an earlier return to the decongested state, lowering the emissions due to the bottleneck caused by the roadworks?
Message sent and received/Message content	X	X	
Reception point / HMI display	X	X	
Speed			X
Acceleration/Deceleration		X	X
Position	X	X	X

Environment - Data Requirements Roadworks Warning	Does the service allow a greater number of platoons to keep their formation?	Do the smoother lane changes have an impact on the surrounding traffic flow and on shockwaves creation and propagation?	Does the CACC system promote an earlier return to the decongested state, lowering the emissions due to the bottleneck caused by the roadworks?
Kilometers out of formation	X		X
Headway or Spacing Policy	X		X
Steering angle		X	
Number of vehicles in the platoon/Platoon length	X	X	X
Fuel consumption	X		

Environment - Field test indicators Roadworks Warning	Does the service allow a greater number of platoons to keep their formation?	Do the smoother lane changes have an impact on the surrounding traffic flow?	Does the CACC system promote an earlier return to the decongested state?
Average Speed			X
Instantaneous acceleration and decelerations		X	X

Environment - Field test indicators Roadworks Warning	Does the service allow a greater number of platoons to keep their formation?	Do the smoother lane changes have an impact on the surrounding traffic flow?	Does the CACC system promote an earlier return to the decongested state?
Lane Change Point	**X**	**X**	
Maximum steering angle		**X**	
Number of platoons able to pass through the roadworks in formation	**X**		
Gap chosen for the lane changing maneuver	**X**	**X**	
Traffic densities beyond which the lane changing maneuver is hindered	**X**	**X**	
Average flow across the bottleneck section			**X**
Disaggregation starting point			**X**
Fuel consumption	**X**		

User Acceptance

Survey's Outputs

The following indicators should be collected after surveys:

- Situation awareness

- Knowledge about the Truck Platooning system and the C-ITS Use Case potentialities
- Problem perception related to the approached roadworks
- Perceived threats for the driver himself or for the workers on the road
- Perceived benefits

Overall future estimated impact KPI (when penetration rate will be higher)

The following Key Performance Indicators (based on EIP list) can be estimated starting from the outputs of field test data or simulation works. Jointed impacts between Truck Platooning, CACC vehicles and the C-ITS service should be evaluated, on the basis of the different market penetration forecasts.

- Change in Journey Time
- Change in Total Time spent by all vehicles in queue
- Change in Road Capacity
- Change in traffic CO_2 or polluting emissions
- Change in noise pollution
- Change in fuel consumption

A.2.2. *In Vehicle Signage – Dynamic Speed Limit Information*

Traffic Efficiency

Data requirements – route parameters – design choices

The following parameters/data should be collected from equipped trucks and communication sources or implemented in a simulation model:

- Message sent and received/Message content – Data logs
- Reception point – Can Bus data and GPS data
- Platoon vehicles Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- Headway or Spacing Policy – source: OEMs choice
- Number of truck platoons among the traffic flow – source: on-road cameras or through modeling works

Field Test Indicators – Modeling outputs

The following parameters should be collected or recorded as model outputs:

- Platoon vehicles Average Speed – source: Can Bus data or GPS data
- Platoon vehicles Speed Standard Deviation - source: Can Bus data

- Platoon vehicles Instantaneous accelerations and decelerations – source: Can Bus data
- Dynamic capacity (i.e., the downstream outflow from traffic congestion) – source: on-road sensors or through modeling
- Time needed for the flow to recover from the congested state – Only through modeling and for different levels of market penetration

Overview of the sub-research questions

Traffic Efficiency - Data Requirements In Vehicle Signage	Is the driver's speed (more) compliant with the suggested speed limit?
Message sent and received/Message content	**X**
Reception point / HMI display	**X**
Speed	**X**
Acceleration/Deceleration	**X**
Position	**X**
Headway or Spacing Policy	**X**
Number of truck platoons among the traffic flow	**X**

Traffic Efficiency - Field test indicators In Vehicle Signage	Is the driver's speed (more) compliant with the suggested speed limit?
Average Speed	X
Speed Standard Deviation	X
Instantaneous acceleration and decelerations	X
Dynamic capacity	X
Time needed for the flow to recover from the congested state	X

Environment

Data requirements – route parameters – design choices

The following parameters/data should be collected from equipped trucks or implemented in a simulation model:

- Message sent and received/Message content – Data logs
- Reception point / HMI display – source: GPS data and Can Bus data
- Platoon vehicles Speed – source: Can Bus data or GPS data
- Platoon vehicles Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- Time Gap Accuracy/Stability – source: Sensors data
- Number of vehicles in the platoon - platoon length

- Environmental features (e.g. Wind speed/direction, temperature, etc.) – source: weather stations
- Average fuel consumption per kilometer – source: Can Bus data

Field Test Indicators – Modeling outputs

The following parameters should be collected or recorded as model outputs:

- Platoon Speed adaptation (difference between the average speed of the vehicle and the speed limit) – source: Can Bus data or GPS data
- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Average flow across the bottleneck section/Dynamic Capacity – source: on-road detectors or through modeling works
- Fuel consumption – source: Can Bus data

Overview of the sub-research questions

Environment - Data Requirements In Vehicle Signage	Is the driver's speed (more) compliant with the suggested speed limit?	Do the informed platoons actually avoid getting stuck in traffic jams?	How does having slower platoons driving in formation upstream the queue impact on the congestion recovery?
Message sent and received/Message content	X	X	X
Reception point / HMI display	X	X	X
Speed	X	X	
Acceleration/Deceleration	X		

Environment - Data Requirements In Vehicle Signage	Is the driver's speed (more) compliant with the suggested speed limit?	Do the informed platoons actually avoid getting stuck in traffic jams?	How does having slower platoons driving in formation upstream the queue impact on the congestion recovery?
Position	X	X	X
Time Gap Accuracy/Stability			X
Number of vehicles in the platoon/Platoon length		X	X
Fuel consumption	X	X	X

Environment - Field test indicators	Is the driver's speed (more) compliant with the suggested speed limit?	Do the informed platoons actually avoid getting stuck in traffic jams?	How does having slower platoons driving in formation upstream the queue impact on the congestion recovery?
Speed Adaptation	X		X
Average Speed	X	X	
Speed Standard Deviation	X		

Environment - Field test indicators	Is the driver's speed (more) compliant with the suggested speed limit?	Do the informed platoons actually avoid getting stuck in traffic jams?	How does having slower platoons driving in formation upstream the queue impact on the congestion recovery?
Instantaneous Accelerations and Decelerations	X	X	
Average flow across the bottleneck section/Dynamic Capacity			X
Fuel consumption	X	X	X

User Acceptance

Survey's Outputs

The following indicators should be collected after surveys:

- Situation awareness
- Knowledge about the Truck Platooning system and the C-ITS use case potentiality
- Perceived benefits

Overall future estimated impact KPI (when penetration rate will be higher)

The following Key Performance Indicators (based on EIP list) can be estimated starting from the outputs of field test data or simulation works. Jointed impacts between Truck Platooning, CACC vehicles and the C-ITS service should be evaluated, on the basis of the different market penetration forecasts.

- Change in Journey Time
- Change in Total Time spent by all vehicles in queue
- Change in Traffic Flow
- Change in Bottleneck Congestion
- Change in Road Capacity
- Change in traffic CO_2 or polluting emissions
- Change in noise pollution
- Change in fuel consumption

A.2.3. *Hazardous Location Notification – Cluster 1: Accident Zone, Slow or Stationary Vehicle, Obstacle on the road, Animal or person on the road*

Traffic Efficiency

Data requirements-route parameters-design choices

The following parameters/data should be collected from equipped trucks and communication sources or implemented in a simulation model:

- Message sent and received/Message content – Data logs
- Reception point/HMI display – Can Bus data and GPS data
- Platoon vehicles Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- Slow vehicle's Speed – source: cameras
- Traffic density – source: on-road detectors or modeling works
- Headway or Spacing Policy – source: OEMs choice
- Number of lanes hindered by the event – source: Message data log
- Platooning vehicles steering angle – source: Can Bus data
- Number of vehicles in the platoon – Platoon length – Position along the platoon

Field Test Indicators – Modeling outputs

The following parameters should be collected or recorded as model outputs:

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Lane change point – source: GPS data
- Maximum steering angle – source: Can Bus data
- Gap chosen for the lane changing maneuver – source: through modeling works or algorithm specifications
- Traffic densities beyond which the lane changing maneuver is hindered – source: through modeling works
- Average flow across the bottleneck section – source: on-road detectors or through modeling works
- Dynamic capacity (i.e., the downstream outflow from traffic congestion) – source: on-road detectors or through modeling works
- Disaggregation starting point – source: GPS data and Can Bus data

- Travel time delay/ Time queued behind the accident zone or the broken down vehicle – source: GPS data

Overview of the sub-research questions

Traffic Efficiency - Data Requirements HLN Cluster 1	How does the lane change point vary (if the lane of the event is specified)	Does the average speed decrease?	Does the service avoid the platoon dissolution
Message sent and received/Message content	X	X	X
Reception point / HMI display	X	X	X
Speed		X	
Acceleration/Deceleration	X	X	
Position	X	X	X
Steering angle	X		
Slow vehicle's speed	X	X	X
Traffic Density	X		

Traffic Efficiency - Data Requirements **HLN Cluster 1**	How does the lane change point vary (if the lane of the event is specified)	Does the average speed decrease?	Does the service avoid the platoon dissolution
Headway or Spacing Policy	X		
Number of vehicles in the platoon – Platoon length	X		X
Number of lanes hindered by the event	X	X	X

Traffic Efficiency – Field Test indicators **HLN Cluster 1**	How does the lane change point vary (if the lane of the event is specified)?	Does the average speed decrease?	Does the service avoid the platoon dissolution?
Average Speed		X	
Speed Standard Deviation		X	
Instantaneous acceleration and decelerations	X	X	
Lane Change Point	X		X

Traffic Efficiency – Field Test indicators HLN Cluster 1	How does the lane change point vary (if the lane of the event is specified)?	Does the average speed decrease?	Does the service avoid the platoon dissolution?
Gap chosen for the lane changing maneuver	X		X
Maximum steering angle	X		
Traffic densities beyond which the lane changing maneuver is hindered	X		X
Average flow across the bottleneck section/Dynamic Capacity			X
Disaggregation starting point			X
Travel time delay/Time queued behind the accident zone		X	X

Safety

Data requirements – route parameters – design choices

The following parameters/data should be collected from equipped trucks and communication sources or implemented in a simulation model:

- Message sent and received/Message content – source: Data logs
- Reception point – source: Can Bus data and GPS data
- Platoon vehicles Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Headway or Spacing Policy – source: OEMs choice
- Platooning vehicles steering angle – source: Can Bus data

- TTC and BTN – source: Sensors data
- Slow vehicle's speed – source: Can Bus data or cameras
- Number of vehicles in the platoon – Platoon length – Position along the platoon

Field Test Indicators – Modeling outputs

The following parameters should be collected or recorded as model outputs:

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Lane change point – source: Can Bus data or GPS data
- Overtaking/Lane change maneuver starting speed – source: Can Bus data
- Gap chosen for the lane changing maneuver – source: through modeling works or algorithm specifications
- Minimum TTC and Minimum BTN/ Number of events involving safety-critical values of BTN and TTC – source: Sensors data
- Disaggregation starting point – source: Can Bus data or GPS data
- Lateral Position Standard Deviation – source: Sensors data

Overview of the sub-research questions

Safety – Data Requirement HLN Cluster 1	How do the instant speed fluctuations change?	Is the lane change maneuver smoother?	Does the service decrease the number of scenarios in which a truck platoon suddenly finds itself stuck behind a slow or stationary vehicle?	Does this cluster of use cases lower the chances of rear-end collision with slow or stationary vehicle?
Message sent and received/Message content	**X**	**X**	**X**	**X**
Reception point	**X**	**X**	**X**	**X**
Acceleration / Deceleration	**X**			**X**

Safety – Data Requirement HLN Cluster 1	How do the instant speed fluctuations change?	Is the lane change maneuver smoother?	Does the service decrease the number of scenarios in which a truck platoon suddenly finds itself stuck behind a slow or stationary vehicle?	Does this cluster of use cases lower the chances of rear-end collision with slow or stationary vehicle?
Speed	**X**	**X**		**X**
Headway or Spacing Policy				**X**
Steering angle		**X**		
Time to Collision or similar metrics		**X**		**X**
Slow vehicle's speed			**X**	**X**
Number of vehicles in the platoon – platoon length		**X**	**X**	

Safety – Field test indicators HLN Cluster 1	How do the instant speed fluctuations change?	Is the lane change maneuver smoother?	Does the service decrease the number of scenarios in which a truck platoon suddenly finds itself stuck behind a slow or stationary vehicle?	Does this cluster of use cases lower the chances of rear-end collision with slow or stationary vehicle?
Average speed			**X**	**X**

Safety – Field test indicators HLN Cluster 1	How do the instant speed fluctuations change?	Is the lane change maneuver smoother?	Does the service decrease the number of scenarios in which a truck platoon suddenly finds itself stuck behind a slow or stationary vehicle?	Does this cluster of use cases lower the chances of rear-end collision with slow or stationary vehicle?
Speed Standard Deviation	**X**	**X**	**X**	**X**
Instantaneous acceleration and decelerations	**X**		**X**	**X**
Lane change point		**X**	**X**	
Overtaking/Lane change maneuver starting speed	**X**	**X**	**X**	
Gap chosen for the lane changing maneuver		**X**	**X**	
Minimum TTC/Number of events involving safety-critical TTC values per km		**X**		**X**
Disaggregation starting point	**X**		**X**	**X**
Lateral position standard deviation		**X**	**X**	

Environment

Data requirements – route parameters – design choices

The following parameters/data should be collected from equipped trucks or implemented in a simulation model:

- Platoon vehicles Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- Reception point – source: GPS data and Can Bus data
- Message sent and received/Message content – source: Data logs
- Headway or Spacing Policy – source: OEMs choices
- Number of vehicles in the platoon – Platoon length – Position along the platoon
- Platooning vehicles steering angle – source: Can Bus data
- Environmental features (e.g. Wind speed/direction, temperature, etc.) – source: weather stations
- Average fuel consumption per kilometer – source: Can Bus data

Field Test Indicators – Modeling outputs

The following parameters should be collected or recorded as model outputs:

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Lane change point – source: GPS data
- Maximum steering angle – source: Can Bus data
- Maximum acceleration value – source: Can Bus data
- Number of platoons able to pass through the hazardous location in formation – source: GPS data
- Gap chosen for the lane changing maneuver – source: Cameras
- Traffic densities beyond which the lane changing maneuver is hindered – source: through modeling
- Average flow across the bottleneck section – source: on-road detectors
- Disaggregation starting point – source: Can Bus data and GPS data
- Fuel consumption – source: Can Bus data

Overview of the sub-research questions

Environment – Data Requirement HLN Cluster 1	Does the service avoid the platoon dissolution?	Do the smoother lane changes have an impact on the surrounding traffic flow and on shockwaves creation and propagation?	How do the instant speed fluctuations change?	Does the average speed decrease?	Does the service decrease the number of scenarios in which a truck platoon suddenly finds itself stuck behind a slow or stationary vehicle or an accident zone?
Message sent and received/Message content	X	X	X	X	X
Reception point	X	X	X	X	X
Acceleration / Deceleration			X		
Speed			X	X	
Headway or Spacing Policy	X	X			
Steering angle		X			X
Environmental features	X				X
Position	X	X	X	X	X

Environment – Data Requirement HLN Cluster 1	Does the service avoid the platoon dissolution?	Do the smoother lane changes have an impact on the surrounding traffic flow and on shockwaves creation and propagation?	How do the instant speed fluctuations change?	Does the average speed decrease?	Does the service decrease the number of scenarios in which a truck platoon suddenly finds itself stuck behind a slow or stationary vehicle or an accident zone?
Number of vehicles in the platoon – platoon length	**X**	**X**			**X**
Fuel consumption	**X**	**X**	**X**	**X**	**X**

Environment – Field test indicators HLN Cluster 1	Does the service avoid the platoon dissolution?	Do the smoother lane changes have an impact on the surrounding traffic flow and on shockwaves creation and propagation?	How do the instant speed fluctuations change?	Does the average speed decrease?	Does the service decrease the number of scenarios in which a truck platoon suddenly finds itself stuck behind a slow or stationary vehicle or an accident zone?
Message sent and received/Message content	**X**	**X**	**X**	**X**	**X**
Reception point	**X**	**X**	**X**	**X**	**X**
Acceleration / Deceleration			**X**		

Environment – Field test indicators HLN Cluster 1	Does the service avoid the platoon dissolution?	Do the smoother lane changes have an impact on the surrounding traffic flow and on shockwaves creation and propagation?	How do the instant speed fluctuations change?	Does the average speed decrease?	Does the service decrease the number of scenarios in which a truck platoon suddenly finds itself stuck behind a slow or stationary vehicle or an accident zone?
Average Speed		X	X	X	
Speed Standard Deviation		X	X		
Instantaneous accelerations and decelerations			X		
Lane change Point	X	X			X
Maximum steering angle	X	X			X
Number of platoons able to pass through the hazardous location	X	X			X
Gap chosen for the lane changing maneuver	X	X			X
Traffic densities beyond which the lane changing maneuver is hindered	X	X			X

Environment – Field test indicators HLN Cluster 1	Does the service avoid the platoon dissolution?	Do the smoother lane changes have an impact on the surrounding traffic flow and on shockwaves creation and propagation?	How do the instant speed fluctuations change?	Does the average speed decrease?	Does the service decrease the number of scenarios in which a truck platoon suddenly finds itself stuck behind a slow or stationary vehicle or an accident zone?
Average flow across the bottleneck section			X	X	X
Disaggregation starting point	X		X		X
Fuel consumption	X	X	X	X	X

User Acceptance

Survey's Outputs

The following indicators should be collected after surveys:

- Situation awareness
- Knowledge about the Truck Platooning system
- Problem perception related to the approached dangerous location
- Perceived threats for the driver himself or for the workers on the road
- Perceived benefits

Overall future estimated impact KPI (when penetration rate will be higher)

The following Key Performance Indicators (based on EIP list) can be estimated starting from the outputs of field test data or simulation works. Jointed impacts between Truck Platooning, CACC vehicles and the C-ITS service should be evaluated, on the basis of the different market penetration forecasts.

- Change in Journey Time
- Change in Total Time spent by all vehicles in queue

- Change in Road Capacity
- Change in traffic CO_2 or polluting emissions
- Change in noise pollution
- Change in fuel consumption

A.2.4. *Hazardous Location Notification – Cluster 2: Traffic Jam Ahead*

Traffic Efficiency

Data requirements – route parameters – design choices

The following parameters/data should be collected from equipped trucks or implemented in a simulation model:

- Message sent and received/Message content – source: Data logs
- Reception point – source: Can Bus data and GPS data
- Platoon vehicles Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- Speed of the flow on the other lanes – source: on-road detectors or modeling works
- Length of the queue – source: on-road detectors or modeling works
- Traffic density – source: on-road detectors or modeling works
- Headway or Spacing Policy – source: OEMs choices
- Number of lanes hindered by the queue – source: Message data log
- Platooning vehicles steering angle – source: Can Bus data
- Number of vehicles in the platoon – Platoon length – Position along the platoon

Field Test Indicators – Modeling Outputs

The following parameters should be collected or recorded as model outputs:

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Lane change point – source: GPS data
- Maximum steering angle – source: Can Bus data
- Gap chosen for the lane changing maneuver – source: through modeling or algorithm specifications
- Traffic densities beyond which the lane changing maneuver is hindered – source: through modeling

- Time needed for the queue to dissolve – Only through modeling
- Travel time delay/ Time the platoon gets stuck behind a queue – source: GPS data
- Dynamic capacity (i.e., the downstream outflow from traffic congestion) – source: on-road detectors or through modeling

Overview of the sub-research questions

Traffic Efficiency – Data Requirement HLN Cluster 2	Is the driver's speed (more) compliant with the suggested speed limit?	How does the lane change point vary? Is the lane change maneuver carried out in a smoother way?	Does the service avoid the platoon from getting stuck behind the queue?
Message sent and received/Message content	X	X	X
Reception point	X	X	X
Acceleration / Deceleration		X	
Speed	X		
Headway or Spacing Policy		X	
Steering angle		X	X
Speed of the flow on the other lane	X	X	X

Traffic Efficiency – Data Requirement HLN Cluster 2	Is the driver's speed (more) compliant with the suggested speed limit?	How does the lane change point vary? Is the lane change maneuver carried out in a smoother way?	Does the service avoid the platoon from getting stuck behind the queue?
Position	X	X	X
Length of the queue			X
Number of lanes hindered by the queue		X	X
Traffic density	X		
Number of vehicles in the platoon – Platoon length		X	X

Traffic Efficiency – Field test indicators HLN Cluster 2	Is the driver's speed (more) compliant with the suggested speed limit?	How does the lane change point vary? Is the lane change maneuver carried out in a smoother way?	Does the service avoid the platoon from getting stuck behind the queue?
Average Speed	X		X
Speed Standard Deviation		X	

Traffic Efficiency – Field test indicators HLN Cluster 2	Is the driver's speed (more) compliant with the suggested speed limit?	How does the lane change point vary? Is the lane change maneuver carried out in a smoother way?	Does the service avoid the platoon from getting stuck behind the queue?
Instantaneous acceleration / deceleration		**X**	
Lane change point		**X**	**X**
Maximum steering angle		**X**	**X**
Gap chosen for the lane changing maneuver		**X**	**X**
Traffic densities beyond which the lane changing maneuver is hindered		**X**	**X**
Time needed for the queue to dissolve	**X**	**X**	**X**
Travel time delay / Time the platoon gets stuck behind a queue	**X**		**X**
Dynamic capacity	**X**	**X**	**X**

Safety

Data requirements – route parameters – design choices

The following parameters/data should be collected from equipped trucks or implemented in a simulation model:

- Message sent and received/Message content – source:Data logs
- Reception point – source: Can Bus data and GPS data
- Platoon vehicles Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Headway or Spacing Policy – source: OEMs choices
- Platooning vehicles steering angle – source: Can Bus data
- TTC and BTN – source: Sensors data

Field Test Indicators – Modeling Outputs

The following parameters should be collected or recorded as model outputs:

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Lane change point – source: GPS data
- Gap chosen for the lane changing maneuver – source: through modeling or algorithm specifications
- Minimum TTC and Minimum BTN/ Number of events involving safety-critical values of BTN and TTC – source: Sensors data
- Lateral Position Standard Deviation – source: Sensors data

Overview of the sub-research questions

Safety – Data requirements HLN Cluster 2	Does this cluster of use cases lower the chances of rear-end collision with the end of a queue?	How do the instant speed fluctuations change?	Is the lane change maneuver smoother?
Message sent and received/Message content	x	x	x

Safety – Data requirements HLN Cluster 2	Does this cluster of use cases lower the chances of rear-end collision with the end of a queue?	How do the instant speed fluctuations change?	Is the lane change maneuver smoother?
Reception point	X	X	X
Acceleration / Deceleration	X	X	X
Speed	X		
Headway or Spacing Policy	X		
Steering angle			X
TTC or similar metrics	X		

Safety – Field test indicators HLN Cluster 2	Does this cluster of use cases lower the chances of rear-end collision with the end of a queue?	How do the instant speed fluctuations change?	Is the lane change maneuver smoother?
Average Speed	X	X	

Safety – Field test indicators HLN Cluster 2	Does this cluster of use cases lower the chances of rear-end collision with the end of a queue?	How do the instant speed fluctuations change?	Is the lane change maneuver smoother?
Speed Standard Deviation	X	X	X
Instantaneous acceleration and decelerations	X	X	X
Lane change point			X
Gap chosen for the lane changing maneuver	X		X
Minimum TTC / Number of events involving safety critical values of TTC per kilometer	X		X
Lateral Position Standard Deviation			X

Environment

Data requirements – route parameters – design choices

The following parameters/data should be collected from equipped trucks or implemented in a simulation model:

- Platoon vehicles Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- Reception point – source: GPS data and Can Bus data
- Message sent and received/Message content – source: Data logs

- Headway or Spacing Policy – source: OEMs choices
- Number of vehicles in the platoon – Platoon length – Position along the platoon
- Platooning vehicles steering angle – source: Can Bus data
- Environmental features (e.g. Wind speed/direction, temperature, etc.) – source: weather stations
- Average fuel consumption per kilometer – source: Can Bus data

Field Test Indicators – Modeling outputs

The following parameters should be collected or recorded as model outputs:

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Lane change point – source: GPS data
- Speed on the other lanes/Difference in speed between the lanes – source: on-road detectors
- Maximum steering angle – source: Can Bus data
- Number of platoons able to pass through the queue – source: GPS data or through modeling
- Gap chosen for the lane changing maneuver – source: Cameras
- Fuel consumption – source: Can Bus data

Overview of the sub-research questions

Environment – Data Requirements HLN Cluster 2	Do the smoother lane changes have an impact on the surrounding traffic flow? (Relevant when the lane occupied by the queue is identified and broadcasted)	How do the instant speed fluctuations change?	How does the presence of truck platoons upstream the hazardous location impact on traffic flow?	Do the informed platoons actually avoid getting stuck in traffic jams? If not, does the informed platoons reach later the congested sections (therefore being stuck for lower time)?
Message sent and received/Message content	**X**	**X**	**X**	**X**

Environment – Data Requirements HLN Cluster 2	Do the smoother lane changes have an impact on the surrounding traffic flow? (Relevant when the lane occupied by the queue is identified and broadcasted)	How do the instant speed fluctuations change?	How does the presence of truck platoons upstream the hazardous location impact on traffic flow?	Do the informed platoons actually avoid getting stuck in traffic jams? If not, does the informed platoons reach later the congested sections (therefore being stuck for lower time)?
Reception point	X	X	X	X
Acceleration / Deceleration	X	X	X	X
Speed	X	X		X
Headway or Spacing Policy	X		X	
Steering angle	X		X	
Position	X	X	X	X
Number of vehicles in the platoon – Platoon length	X		X	
Fuel consumption	X	X	X	X

Environment – Data Requirements HLN Cluster 2	Do the smoother lane changes have an impact on the surrounding traffic flow? (Relevant when the lane occupied by the queue is identified and broadcasted)	How do the instant speed fluctuations change?	How does the presence of truck platoons upstream the hazardous location impact on traffic flow?	Do the informed platoons actually avoid getting stuck in traffic jams? If not, does the informed platoons reach later the congested sections (therefore being stuck for lower time)?
Environmental features			X	X

Environment – Field test indicators HLN Cluster 2	Do the smoother lane changes have an impact on the surrounding traffic flow? (Relevant when the lane occupied by the queue is identified and broadcasted)	How do the instant speed fluctuations change?	How does the presence of truck platoons upstream the hazardous location impact on traffic flow?	Do the informed platoons actually avoid getting stuck in traffic jams? If not, does the informed platoons reach later the congested sections (therefore being stuck for lower time)?
Average Speed		X	X	X
Speed Standard Deviation	X	X	X	X
Instantaneous accelerations and decelerations	X	X	X	
Lane change point	X			X

Environment – Field test indicators HLN Cluster 2	Do the smoother lane changes have an impact on the surrounding traffic flow? (Relevant when the lane occupied by the queue is identified and broadcasted)	How do the instant speed fluctuations change?	How does the presence of truck platoons upstream the hazardous location impact on traffic flow?	Do the informed platoons actually avoid getting stuck in traffic jams? If not, does the informed platoons reach later the congested sections (therefore being stuck for lower time)?
Speed on the other lanes/Difference in speed between the lanes	X			X
Maximum steering angle	X			
Maximum braking capability		X	X	X
Number of platoons able to pass through the queue	X		X	X
Gap chosen for the lane changing maneuver	X			X
Fuel Consumption	X	X	X	X

User Acceptance

Survey's Outputs

The following indicators should be collected after surveys:

- Situation awareness
- Knowledge about the Truck Platooning system
- Problem perception related to the approached queue

Overall future estimated impact KPI (when penetration rate will be higher)

The following Key Performance Indicators (based on EIP list) can be estimated starting from the outputs of field test data or simulation works. Jointed impacts between Truck Platooning, CACC vehicles and the C-ITS service should be evaluated, on the basis of the different market penetration forecasts.

- Change in Journey Time
- Change in Total Time spent by all vehicles in queue
- Change in Road Capacity
- Change in traffic CO2 or polluting emissions
- Change in noise pollution
- Change in fuel consumption

A.2.5. Hazardous Location Notification – Cluster 3: Weather Condition Warning – Temporary Slippery Road

Traffic Efficiency

Data requirements – route parameters – design choices

The following parameters/data should be collected from equipped trucks and communication sources or implemented in a simulation model:

- Message sent and received/Message content – source: Data logs
- Reception point – source: Can Bus data and GPS data
- Platoon vehicles Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Maximum acceleration and deceleration achievable by each truck
- Position – source: GPS data
- Traffic density – source: on-road detectors or cameras, through modeling works
- Headway or Spacing Policy – source: by design
- Number of lanes hindered by the event – source: Message data log
- Platooning vehicles steering angle – source: CAN Bus data
- Road grade – source: known physical feature of the infrastructure
- Signal coverage
- Number of vehicles in the platoon – Platoon length – Position along the platoon

Field Test Indicators – Modeling outputs

The following parameters should be collected or recorded as model outputs:

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Lane change point – source: GPS data
- Maximum steering angle – source: Can Bus data
- Gap chosen for the lane changing maneuver
- Traffic densities beyond which the lane changing maneuver is hindered
- Time Gap Accuracy/Stability or Error in Spacing – source: Radar and GPS
- Disaggregation starting point

Overview of the sub-research questions

Traffic Efficiency – Data Requirement HLN Cluster 3	Does the information forwarded by the service allow the platoon to keep its formation, regardless of the adverse weather conditions?	Does the information forwarded by the service allow smoother disaggregation maneuvers?	Does the average speed decreases?	Does the information forwarded by the service allow the platoon avoid the spillage by changing lane in advance?	Does the information forwarded by the service avoid sudden braking by the platoon?
Message sent and received/Message content	X	X	X	X	X
Reception point	X	X	X	X	X
Acceleration / Deceleration	X	X			X
Speed	X		X	X	X

Traffic Efficiency – Data Requirement HLN Cluster 3	Does the information forwarded by the service allow the platoon to keep its formation, regardless of the adverse weather conditions?	Does the information forwarded by the service allow smoother disaggregation maneuvers?	Does the average speed decreases?	Does the information forwarded by the service allow the platoon avoid the spillage by changing lane in advance?	Does the information forwarded by the service avoid sudden braking by the platoon?
Headway or Spacing Policy	X	X			
Steering angle				X	
Maximum acceleration and deceleration achievable by each truck	X	X			
Position	X	X	X	X	X
Traffic density		X	X		X
Number of lanes hindered by the event				X	
Road Grade	X	X	X		
Signal coverage	X			X	

Traffic Efficiency – Data Requirement HLN Cluster 3	Does the information forwarded by the service allow the platoon to keep its formation, regardless of the adverse weather conditions?	Does the information forwarded by the service allow smoother disaggregation maneuvers?	Does the average speed decreases?	Does the information forwarded by the service allow the platoon avoid the spillage by changing lane in advance?	Does the information forwarded by the service avoid sudden braking by the platoon?
Number of vehicles in the platoon – Platoon length	X	X		X	

Traffic Efficiency – Field test indicators HLN Cluster 3	Does the information forwarded by the service allow the platoon to keep its formation, regardless of the adverse weather conditions?	Does the information forwarded by the service allow smoother disaggregation maneuvers?	Does the average speed decreases?	Does the information forwarded by the service allow the platoon avoid the spillage by changing lane in advance?	Does the information forwarded by the service avoid sudden braking by the platoon?
Average Speed			X		
Speed Standard Deviation		X			X
Instantaneous acceleration / deceleration	X	X			X
Lane change point				X	
Maximum steering angle				X	

Traffic Efficiency – Field test indicators HLN Cluster 3	Does the information forwarded by the service allow the platoon to keep its formation, regardless of the adverse weather conditions?	Does the information forwarded by the service allow smoother disaggregation maneuvers?	Does the average speed decreases?	Does the information forwarded by the service allow the platoon avoid the spillage by changing lane in advance?	Does the information forwarded by the service avoid sudden braking by the platoon?
Gap chosen for the lane changing maneuver				**X**	
Traffic densities beyond which the lane changing maneuver is hindered				**X**	
Time Gap Accuracy/Stability	**X**	**X**	**X**	**X**	**X**
Disaggregation starting point		**X**			

Safety

Data requirements – route parameters – design choices

The following parameters/data should be collected from equipped trucks and communication sources or implemented in a simulation model:

- Message sent and received/Message content – source: Data logs
- Reception point – source: Can Bus data and GPS data
- Platoon vehicles Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Road grade – source: known physical feature of the infrastructure
- Headway or Spacing Policy – source: by design
- Maximum acceleration and deceleration achievable by each truck – source: feature known by the OEM
- Number of lanes hindered by the event – source: Message data log

- Signal coverage
- Platooning vehicles steering angle – source: CAN Bus data
- TTC, BTN and target acceleration of the preceding vehicle – source: CAN Bus data

Field Test Indicators – Modeling outputs

The following parameters should be collected or recorded as model outputs:

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Lane change point – source: Can Bus data
- Gap chosen for the lane changing maneuver – source: sensors data
- Minimum TTC and Minimum BTN/ Number of events involving safety-critical values of BTN and TTC – source: sensors data
- Time Gap Accuracy/Stability or Error in Spacing – source: Radar and GPS
- Disaggregation starting point – source: Can Bus data and GPS

Overview of the sub-research questions

Safety – Data Requirement HLN Cluster 3	Does the platoon dissolve or adapt its headway before reaching the adverse weather area?	Is the disaggregation maneuver carried out in a smoother and safer way?	Does an improved situational awareness help the drivers identify dangers difficult to perceive visually?	Does the information provided help the platooning algorithm or the drivers chose when dissolve the platoon?	Is the lane change maneuver smoother?	Does the average speed decrease?	Does the forwarded information prevent some platoons from completely stopping before the compromised section?
Message sent and received/ Message content	**X**	**X**	**X**	**X**	**X**	**X**	**X**
Reception point	**X**	**X**	**X**	**X**	**X**	**X**	**X**
Acceleration / Deceleration		**X**			**X**		

Safety – Data Requirement HLN Cluster 3	Does the platoon dissolve or adapt its headway before reaching the adverse weather area?	Is the disaggregation maneuver carried out in a smoother and safer way?	Does an improved situational awareness help the drivers identify dangers difficult to perceive visually?	Does the information provided help the platooning algorithm or the drivers chose when dissolve the platoon?	Is the lane change maneuver smoother?	Does the average speed decrease?	Does the forwarded information prevent some platoons from completely stopping before the compromised section?
Speed	X		X			X	
Headway or Spacing Policy	X	X		X			
Steering angle					X		
Maximum acceleration and deceleration achievable by each truck	X	X	X				
Position	X	X	X	X	X	X	X
TTC or similar metrics	X	X			X		
Number of lanes hindered by the event				X	X		X
Road Grade	X		X				

Safety – Data Requirement HLN Cluster 3	Does the platoon dissolve or adapt its headway before reaching the adverse weather area?	Is the disaggregation maneuver carried out in a smoother and safer way?	Does an improved situational awareness help the drivers identify dangers difficult to perceive visually?	Does the information provided help the platooning algorithm or the drivers chose when dissolve the platoon?	Is the lane change maneuver smoother?	Does the average speed decrease?	Does the forwarded information prevent some platoons from completely stopping before the compromised section?
Number of vehicles in the platoon – Platoon length	**X**	**X**	**X**	**X**	**X**		**X**

Safety – Field test indicators HLN Cluster 3	Does the platoon dissolve or adapt its headway before reaching the adverse weather area?	Is the disaggregation maneuver carried out in a smoother and safer way?	Does an improved situational awareness help the drivers identify dangers difficult to perceive visually?	Does the information provided help the platooning algorithm or the drivers chose when dissolve the platoon?	Is the lane change maneuver smoother?	Does the average speed decrease?	Does the forwarded information prevent some platoons from completely stopping before the compromised section?
Average Speed			**X**	**X**		**X**	
Speed Standard Deviation		**X**	**X**				**X**
Instantaneous acceleration and decelerations	**X**	**X**	**X**		**X**		
Lane change point					**X**		**X**
Gap chosen for the lane changing maneuver		**X**			**X**		**X**

Safety – Field test indicators HLN Cluster 3	Does the platoon dissolve or adapt its headway before reaching the adverse weather area?	Is the disaggregation maneuver carried out in a smoother and safer way?	Does an improved situational awareness help the drivers identify dangers difficult to perceive visually?	Does the information provided help the platooning algorithm or the drivers chose when dissolve the platoon?	Is the lane change maneuver smoother?	Does the average speed decrease?	Does the forwarded information prevent some platoons from completely stopping before the compromised section?
Minimum TTC / Number of events involving safety critical values of TTC per kilometer		X	X		X		
Time Gap Accuracy / Stability	X	X					X
Disaggregation starting point	X	X	X	X			X

Environment

Data requirements – route parameters – design choices

The following parameters/data should be collected from equipped trucks or implemented in a simulation model:

- Platoon vehicles Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- Reception point – source: GPS data and Can Bus data
- Message sent and received/Message content – Data logs
- Headway or Spacing Policy – source: Can Bus data
- Road Grade – source: known physical feature of the infrastructure
- Number of vehicles in the platoon – Platoon length – Position along the platoon
- Platooning vehicles steering angle – source: Can Bus data
- Environmental features (e.g. Wind speed/direction, temperature, etc.) – source: by records on site
- Average fuel consumption per kilometer – source: Can Bus data

Field Test Indicators – Modeling outputs

The following parameters should be collected or recorded as model outputs:

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Lane change point – source: GPS data
- Speed on the other lanes/Difference in speed between the lanes – source: on-road detectors
- Maximum steering angle – source: Can Bus data
- Maximum braking capability – source: Can Bus data
- Number of platoons able to pass through the spillage/adverse weather condition – source: Can Bus data
- Number of platoons rerouted – source: GPS
- Time Gap Accuracy/Stability or Error in Spacing – source: Radar and GPS
- Gap chosen for the lane changing maneuver – source: Cameras
- Fuel consumption – source: Can Bus data

Overview of the sub-research questions

Environment – Data Requirements HLN Cluster 3	Does the information forwarded by the service allow the platoon to keep its formation, regardless of the adverse weather conditions or liquids on the road?	Does the platoon driving impact less on the surrounding traffic flow?
Message sent and received/Message content	**X**	**X**
Reception point	**X**	**X**
Acceleration / Deceleration	**X**	**X**

Environment – Data Requirements HLN Cluster 3	Does the information forwarded by the service allow the platoon to keep its formation, regardless of the adverse weather conditions or liquids on the road?	Does the platoon driving impact less on the surrounding traffic flow?
Speed	**X**	**X**
Headway or Spacing Policy	**X**	**X**
Steering angle	**X**	**X**
Position	**X**	**X**
Number of vehicles in the platoon – Platoon length	**X**	
Fuel consumption	**X**	**X**
Road Grade	**X**	**X**
Environmental features	**X**	

Environment – Field test indicators HLN Cluster 3	Does the information forwarded by the service allow the platoon to keep its formation, regardless of the adverse weather conditions or liquids on the road?	Does the platoon driving impact less on the surrounding traffic flow?
Average Speed	**X**	**X**
Speed Standard Deviation	**X**	**X**
Instantaneous accelerations and decelerations	**X**	**X**
Lane change point	**X**	**X**
Speed on the other lanes/Difference in speed between the lanes	**X**	**X**
Maximum steering angle	**X**	**X**
Maximum braking capability	**X**	**X**
Number of platoons able to pass through the spillage/adverse weather condition	**X**	**X**
Number of platoons rerouted	**X**	**X**

Environment – Field test indicators HLN Cluster 3	Does the information forwarded by the service allow the platoon to keep its formation, regardless of the adverse weather conditions or liquids on the road?	Does the platoon driving impact less on the surrounding traffic flow?
Time Gap Accuracy/Stability	X	X
Gap chosen for the lane changing maneuver	X	X
Fuel consumption	X	X

User Acceptance

Survey's Outputs

The following indicators should be collected after surveys:

- Situation awareness
- Knowledge about the Truck Platooning system
- Problem perception related to reduced headway and adhesion values
- Trust in the system reliability and capacity to face weather-related conditions

Overall future estimated impact KPI (when penetration rate will be higher)

The following Key Performance Indicators (based on EIP list) can be estimated starting from the outputs of field test data or simulation works. Jointed impacts between Truck Platooning, CACC vehicles and the C-ITS service should be evaluated, on the basis of the different market penetration forecasts.

- Change in Journey Time
- Change in number of crashes/severity of crashes
- Change in number of fatalities
- Change in traffic CO2 or polluting emissions

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