Evaluation approach for a combined implementation of Day 1 C-ITS and Truck Platooning

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***Abstract*— With the advance of automation in the field of transportation, the number of emerging systems that are going to be deployed on the European roads is growing fast. The aim of C-Roads Italy, part of the Europe-wide C-Roads Project, is to evaluate the impacts on public roads and the feasible operational modes of Truck Platooning, when jointly implemented with Day 1 C-ITS. This paper firstly reports an extended summary of the available bibliography on Truck Platooning, focused on the assessment of the implementation scenario presented as an example in Section IV. The literature review is necessary to investigate the more promising implementation schemes in the short term on the European area and the system expected impacts when deployed as a stand-alone service. Then, the evaluation methodology that is currently being drafted in the activity of C-Roads Italy is described, aimed to assess the jointed impact of Day 1 C-ITS services and Truck Platooning. Finally, a meaningful example of the approach for the evaluation of the jointed implementation of Truck Platooning and C-ITS services is presented, considering one of the use cases of the Road Works Warning Service, as defined in the current version of the C-Roads documents.**

Keywords—Truck Platooning, C-ITS, evaluation, CACC, heavy vehicle, impact assessment, cooperative services, freight transport

I. Introduction

Truck Platooning has still to become a reality on public roads. This means that no legal framework exists and that, to evaluate the impacts of the system, the most likely level of automation, features, inputs and coordination schemes for Truck Platooning must be defined. To support this activity, a considerable bibliographical review has been carried out as a first step for an Ex-Ante report, to define the most accepted and common values and findings in literature about the main subjects such as, for example, fuel efficiency, platoon's features, driving behaviour etc. An overview of this literature study is presented in section II. Once defined the most likely implementation scenarios in the short term, an evaluation methodology was designed to assess the impact of the jointed implementation of these scenarios with the Day 1 C-ITS services. Four impact areas were considered: Traffic Efficiency, Safety, Environment and User Acceptance. For each one of these areas, a set of research and sub-research questions was drafted, and the evaluation methodology was defined and presented in section III. Once the method is presented, an example is showed in section IV, about the evaluation of the jointed impacts of Truck Platooning and one of the use cases defined by C-Roads for the Road Works Warning service.

II. Bibliographical review

Truck Platooning is a set of heavy vehicles that, using 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 to the following ones. Information sent this way includes accelerations and decelerations, location, sudden braking and target speed. 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. Both longitudinal and lateral control can currently be entrusted to the automation, depending on the level of automation planned and the equipment installed on the trucks (NHTSA classification, [1]). The area of interest reported in this part of the paper are the one needed to draft the assessment methodology presented as an example in Section III, while in the C-Roads Italy activity a wider bibliography is analysed.

A. CACC and string stability

When the longitudinal control is entrusted to the automation by the means of the CACC, a truck platoon is able to start an anticipatory braking actions, nullifying human action and reaction time in the following vehicles which involves great benefits for the road outflow and traffic efficiency, as stated, for example, in [2]. A review focused on the improvement of traffic flow due to the CACC system was carried out in [3], accounting also the potential of V2V and V2I communications. Another paper that addresses this topic is [4]. The authors designed a CACC system and evaluated its impacts on congestion, considering the application on Truck Platooning. In this paper the contribution of V2V communications grants the possibility to share information about the acceleration of the preceding vehicles. In this way the perturbations are dampened and the headway stands still without dangerous oscillation (string-stable behaviour). A numerical value for the headway, equal to 0,7 s, is determined as string stable resulting from both tests and simulations. An element 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 subject is examined in [5], where a multi-layer approach of the CACC system is presented. This paper [5] accounts for critical scenarios like different engine capacities, maximum braking values, communication delays, different loaded weights and slope effects on the platoon maintenance and on string stability. Different values for maximum acceleration between trucks, can cause the platoon dissolution when on up-hill traits. The subject is also investigated in [6] where the author's considerations following Daimler's participation to the European Truck Platooning Challenge are presented. Many numerical values regarding the system deployed are reported (e.g. the headway of 15 m, the minimum following distance of 7,53 m or the communication delay considered equal to 0,1 s). With these parameters, the authors obtained the minimum rate between the deceleration capacity of two vehicles in the platoon, equal to 0,883.

Although different algorithms and parameters of the CACC can change how much the truck platoon affects the surrounding traffic flow, the expected impacts are an augmented capacity of the infrastructure and a smoother driving. The augmented capacity arises from a more efficient use of the infrastructure, achieved thanks to the reduced headways. A platoon of four trucks can take up 110 meters while four trucks without CACC can occupy 142 – 163 meters. In [7] the impacts of CACC-equipped heavy vehicles on the traffic flow are investigated. The simulations carried out and the traffic data used concerned a section of the interstate highway 85 in the Auburn-Opelika area and the results obtained showed how, as the traffic volume increases, the benefits of the CACC are greater on the traffic flow and the travel time decreases. This however is not relevant in case of free flow or completely congested flow. The results show that a relationship subsists between the average speed and the headway chosen: as the headway drops, the grater the market penetration the higher the average speed achieved, regardless of the traffic volumes.

B. Aerodynamic benefits and fuel savings

Different headway values affect not only Traffic Efficiency, but also fuel consumption. Travelling in platoon formation, implies fuel savings for each vehicle involved and resulting environmental benefits. It is important to note that fuel costs account, on average, for 30% of a truck's operational costs [8]. Fuel savings are achieved thanks to the reduced air drag value between the trucks, due to the shorter headway that won't allow the creation of vortex between the vehicles. This implies that the drag that the engine must overcome is lesser and so is fuel consumption. In [9] studies are cited, in which the consumption due to the air resistance can reach up to 50%. It is stressed that such a value represents just the potentialities, since the result itself depends on the atmospheric conditions, air density values, traffic conditions, speeds and headways, etc. The authors also report that road transport is responsible for at least 72% of emissions in Europe, a quarter of which is attributable to freight transport. In the research project [10] was assessed the fuel consumption in two Class 8 tractor-trailer combinations platooned together. This result was compared with the standalone fuel consumption. The spatial headways used during the tests can be converted in time gaps between 0,2 and 0,8 seconds. A result worth noticing is how the temperature of the coolant increases as the headway decrease; 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 in choosing an optimal headway value. A similar effect is mentioned in [[11] and [12], even if with low incidence and probability. By the numerical output obtained in [10], it can be derived how higher wind speeds increase the fuel savings for the leading vehicle while lower temperatures reduce that value. The maximum reductions in fuel consumption were 5,3% for the leading vehicle and 9,7% for the following vehicle but the authors have pointed out how these values were not obtained during the same test. These values are also in line with the ones reported in [13]: 4% for the leading vehicle, 10% for the second one and 14% for the last one in a platoon of three. In literature, many other values of reductions in fuel consumption are reported. It seems appropriate to list few to give an order of magnitude for the phenomenon. In [11], for example, it's clearly stated how, in a platoon composed of two trucks, the following ones obtains a fuel reduction of 8-13% while the leading one achieve values of 2-8%. As an approximation, in this work, a value of 0,25 litre per kilometre is considered and the reductions are equal to 2-3,3 L per 100 km for the following vehicle. Moreover, a great number of studies focusing on the benefits of a Platooning Service Provider can be found, many of which assumes a mean reduction in fuel consumption for the whole platoon. In [14] a 10% reduction is reported for the following vehicle while the reduction for the leading one is neglected; the same value is assumed in [15] and in [16] 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) [17]. In [18] 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 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 [19], where, again, a 10% fuel saving is reported and in [9] where the fuel saving is considered equal to 9-15%. In [8] some results of SARTRE "D.4.3 Report on Fuel Consumption" are listed: 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%. (…) These fuel savings correspond to a reduction of the emission of CO_2 by 5% to 10%." Similar ranges are considered in [20], where a range of 5-15% is reported, or in [21], where fuel savings range from 2% up to 12% with a spatial gap of 20 m. In the designing of a business model for Truck Platooning, the COMPANION project accounted for lower values in fuel savings, considering 5% for each vehicle [22]. Other values lower than average are the one considered in [23], still equal to 5%, and in [24], equal to 6,5% (driving at highway speed with 1 s time gap). It is still not possible to define a single value or a relation that allows the assessment of reductions in fuel emissions. This is because that value does not depend just on the features of the platoon (i.e. headway, speed, number of vehicles, position across the platoon) but also on the environmental features (i.e. temperature, air density, wind speed, ...), social behaviour, surrounding traffic, slope and so on. In the Ex Ante drafted as an activity of C-Roads Italy, though, the essential factors to consider while defining fuel consumption are listed, highlighting the relationship between each one and how they impact fuel consumption. Also, a methodology to evaluate fuel consumption and environmental benefits bound to Truck Platooning jointly implemented with Day 1 C-ITS services is presented.

C. Truck Platooning and the surrounding traffic flow

Another relevant subject examined in the literature review concerns the relevant maneuvers carried out by the Truck Platoon and impacting the surrounding traffic flow. A Truck Platoon travelling on a public road will face multiple challenges in its interaction with traditional surrounding traffic. These challenges include its formation, disaggregation, lane changing maneuvers and overtaking maneuvers. These interactions have a double effect, because they decrease benefits within the platoon and for the participating vehicles, and they also have an impact on the surrounding traffic flow, on its stability and on the driving smoothness, for example. A relevant paper about the formation maneuver is [16], where the automatic formation of vehicle platoons on a Swedish highway is analysed, considering both the coordination strategies and the potential delays caused by the surrounding traffic flow. The paper identifies an optimal point for the merging of two platooning trucks and the point beyond which the platoon formation is no more fuel efficient when compared to the driving alone situation, to account for delays imposed by the surrounding traffic flow. The outputs of the simulations are the delays in the platoon formation corresponding to the three different levels of traffic densities simulated. The distance driven beyond the optimal merge point turns out to be increased respectively by 4%, 20% and 45%. The authors consider these delays caused by the low leading vehicle's speed that creates a moving bottleneck effect among the other vehicles. These, then, queue between the two heavy vehicles and hinder the platoon formation. In the last part of the article, an experiment carried on a public highway between Hallunda and Moraberg is described. In [25] a paragraph is dedicated to the influence of traffic on HDV platoon formation, considering the same traffic flow densities of [16] (11-15-19 veh/lane/km) but different speeds of the leading vehicle (70 km/h, 75 km/h, 80 km/h). The ideal platoon formation time is calculated as a function of d, the initial distance between the two trucks, v_2, the speed of the following vehicle and v_1, the speed of the leading one. From the simulation appears that, in light traffic, the delays are almost negligible (compared to the baseline values of 0.15 h, 0.2 h, 0.3 h 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, these percentages become 83%, 72% and 48%. The simulations in this work seem to prove that the deceleration of the leading vehicles does not reduce the time needed to form the platoon. In [26] the authors present an approach that considers both the possibility to let the following vehicle accelerate or the leading one decelerate to form a platoon. The hybrid approach proposed includes an algorithm that can account also for modification of the platoon in response to environmental changes. [25] analyses the disaggregation maneuver and its interactions with the surrounding traffic flow at a highway off-ramp area. When the platoon does not disaggregate, the average speed in the left lane decreases until the platoon approaches the off-ramp area. If the platoon dissolves in time, the average speed of the right lane decreases rapidly in the beginning of platoon disaggregation due to the deceleration of platoon members, like mentioned above. The platoon dissolution lets vehicles on the left lane find gaps to change lane and be ready to leave the road branch. The increase in average speed of the left lane can be up to 8% compared with the no-disaggregation case. In [27] the cut-in performed by external vehicles is analysed to assess the fuel consumption resulting from the platoon dissolution. The number of those manoeuvres 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 causes a loss of 0,1 litre/100 km in the fuel saving. This value should be considered as an example: the number of cut-ins is also related to external factors like the surrounding traffic flow, the headway maintained, cultural influences. An approach that aims to mitigate the cut-in impact on Truck Platooning benefits is presented in [28], where a machine learning algorithm in the Support Vector Regression model is considered to improve the safety of Truck Platooning by predicting the behaviour 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 fall-back option when an external vehicle insert itself between two close trucks. This work holds an added value being based on naturalistic driving data part of the TNO Streetwise scenario database. Through different experiments the author evaluated the performance of an optimised direct hybrid recursive forecast (compared to other forecasting strategies). About the ramp areas, it can be stated that they are one of the most critical point for Truck Platooning. Interesting works mentioning or facing these sections across the infrastructure are [25], [29], [30], for example. In [31] V2V and V2I communications are exploited to ease the merging maneuvers of an intruding vehicle meaning to take an exit ramp. The strategy adopted by the authors to mitigate the risks accounts for the platoon to dynamically change the headway held by vehicles, 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 by steps. In [32], the impact of Truck Platooning at on-ramp areas are analysed, concerning both Traffic Efficiency and Safety.

Two approaches are considered: the creation of gaps in the platoon to allow vehicles to merge and the lane changing strategy. From the simulation results, the yielding strategy seems to solve the merging problem at on-ramp areas. The lane change approach reduces merging problems only for congested scenarios; 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.

D. Safety of the system

Another relevant area of investigation concerns Safety-related parameters in a truck platoon. 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 he is in the driving loop, the time to respond to a CACC system failure is too short for human perception. Thus, the driver can't be considered a safe fall-back solution. This is especially true for reduced headways. It should be defined what is the threshold under which the driver can no longer be considered responsible for the longitudinal truck behaviour. To face this issue, in [21], a fail-operational truck platooning architecture is designed considering headway equal to 0.5 s or lower. Also, lateral control is entrusted to the Lane Keep Assist, falling above the L2 automation level. Lastly, the safety for a two Truck Platooning system is assessed by the means of a Hazard and Risk Analysis able to identify risks regarding the steering, braking and acceleration maneuver. The functional safety of the system is analysed complying with the ISO-26262 standard. [33] 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. Other works that face or consider the implications of transmission delays or differences in braking capabilities among the vehicles are [6], [17], [32].

III. Evaluation Methodology

The bibliographical review reported is part of the Ex-Ante evaluation for truck platoon carried out within C-Roads Italy. Beside this approach, an assessment method will be drafted, suitable for the evaluation of Truck Platooning and combined truck platoons and C-ITS services, both in field tests and in the following modelling studies, aimed to assess future KPIs.

This evaluation method deals with four impact areas: Traffic Efficiency, Safety, Environment and User Acceptance. The methodology is designed to analyze how the systems interact and to define how to maximize their benefits. The scenarios considered for the Truck Platooning implementation mostly refers to the short term and it is based on the bibliographical review. Mostly mono-brand truck platoons on public roads (i.e. highways) and falling in the L2 or L3 levels are considered. The evaluation concerns platoons of two, three or four vehicles at most and no dedicated lane or other adaptations of the infrastructure are considered. For the Day 1 C-ITS considered relevant in their joint implementation with Truck Platooning, the latest version of the C-Roads paper defining the use cases was considered. The approach is based on "Research and Sub-Research Questions" and follows FESTA Handbook (Fot-Net 2017) [34].

- Research Question: "Does the C-ITS service allow the platoon to keep its formation for an increased number of kilometers and/or time?". The effect of the C-ITS service on the smoothness of maneuvers and 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 service outputs.

- Examples of Sub Research Questions could be "Does the C-ITS service allow the platoon to maintain its formation?" or "The platoon changes its behaviour in response to a C-ITS service?" The changes of the parameters that characterise the service functioning/platoon driving are investigated for each relevant scenario; data requirements are mentioned.

Also, suggested methods and tools to quantify the impact of the jointed implementation on the four impact areas listed above are mentioned, referring to the bibliographical review. Parameters useful as output and how an evaluator could measure them is described. To define the contribution of the Ex Ante Evaluation, it is important to highlight that it is not possible to obtain numerical results about the jointed implementation of Truck Platooning and C-ITS services. Since these two elements are not yet implemented on public roads (with some exceptions about C-ITS projects and corridors) the bibliographical framework that could be used to specifically assess the jointed impacts is still lacking or scarce. Another important consideration about the work presented in this paper is that the way to investigate in depth each scenario, which data requirements to meet and output indicators to measure are choices left to the evaluator, as function of the test specificities and also of the regional features. This methodology is designed to be suitable for general scenarios and it is not referred to specific field tests or modelling works that will be carried out in the C-Roads Italy activities (during which there will certainly be field tests but not all the subjects listed in the Ex Ante will be evaluated).

IV. Example: Road Works Warning & Truck Platooning

Basing on what is stated in [35], the service is intended to provide warnings to road users approaching roadworks. The Use Case reported as an example is: *Closure of part of a lane, whole lane or several lanes*. The benefits that the service alone is meant to achieve are mainly an increased safety and reduced number of collisions near road works, but improvements in Traffic Efficiency and Environment could also be expected. For a Truck Platoon, some specificities exist. As confirmed by the bibliographical review, in fact, the lane change maneuver can be considered critical for platoons of heavy vehicles from the Traffic Efficiency, Environmental and Safety point of view.

A. *Traffic Efficiency*

The suggested research question is: "Does the information forwarded in advance change the platoon behavior in a way that is beneficial for the whole traffic flow?". Roadworks are a critical stretch on the road, along which vehicles travel with an increased density and reduced velocities. Congestion arises faster and propagates upstream easier. In such a critical scenario an element like a Truck Platoon can worsen the congestion level and be forced to dissolve, losing the benefits deriving from the in-formation driving and possibly finding itself unable to reform for many kilometres downstream the roadworks. An earlier notification about the lane closure can let the platoon pass without dissolving or, at least, bring forward the dissolution 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. To evaluate the impacts, sub-research questions are drafted:

- 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?
- Is the platoon lane changing manoeuvre smoother thanks to the received information?
- Is the platoon dissolution accomplished in a more efficient way? Does the platoon dissolve with sufficient advance to let some of the single trucks change lane before reaching the roadworks?
- Does the forwarded information allow the platoon to keep its formation?

B. *Safety*

The suggested research question is: "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?". Improved situation awareness about the roadworks position and its features 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, it decreases the likelihood of abrupt maneuvers performed by the truck drivers to change lane. To evaluate the impacts, the following sub-research questions are drafted:

- Is the platoon lane changing maneuver smoother thanks to the received information?
- Is the platoon speed more homogeneous?
- Does a L3 platoon dissolve if the information about the roadworks topology can hinder the lateral control (e.g. unsuitable lane markings, road cones, etc.)?

C. *Environment*

The suggested research question is: "Does the information granted by the service promote a more efficient driving both from platooned trucks and human-driven vehicles interacting with the platoon?". The same scenario described in the Traffic Efficiency research question is applicable for the Environment impact area. An earlier notification (or a more intrusive and detailed one) 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, increased situation awareness can ease the lane-changing maneuver performed by the platoon and reduce its negative effects on the surrounding traffic flow. To evaluate the impacts, sub-research questions are drafted:

- 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 ad propagation?

Another research question useful to assess environmental impacts is: "Does the CACC system promote an earlier return to the decongested state, lowering the emissions due to the bottleneck caused by the roadworks?". This research question is based on the CACC properties presented in the related literature review. For each extra platoon that the Use Case manages to let through, compared to a baseline scenario, a positive impact on the flow state and, therefore, on the level of emission can be achieved.

D. *User Acceptance*

The suggested research questions are two. "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. Despite many solutions consider the view of the front vehicle camera 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. The second research question is: "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, does not 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.

V. CONCLUSION

In the Ex-Ante discussed in this paper, for each of the sub-questions in the four impact areas, a brief description is given based on the bibliographical review. Then, the most common assessment instrument applicable, the data requirements and the indicators suggested are listed to guide the evaluator in the design of field tests or modeling works. It is important to note that the contribution of the Ex-Ante evaluation work is a framework able to guide evaluators in their work, suggesting the most common research directions based on the bibliographical review. No aspect of the suggested methodology is meant to be prescriptive, though. Each part of it, in fact, can be adapted on the basis of the situation, of the evaluation activity carried out or of the regional features, just to name a few. This work, for example, accounted for specificities of the Italian situation within C-Roads and the defined evaluation methodology was employed to assess the impacts of another innovative transport system: Highway Chauffeur. After a corresponding bibliographical research about the topic, a method to assess the jointed impact of Highway Chauffeur, Truck Platooning and C-ITS services has been drafted and will be the starting point for the evaluation activities concerning the field tests carried out in Italy within C-Roads. Besides, the set of analysis for each Day 1 service is carried out in a consistent and systematic way, encouraging the development of future researches about other C-ITS services and their interaction with truck platooning and the highway chauffeur system.

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