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EXECUTIVE SUMMARY

Context and need of a multi-brand platooning project

Context

Platooning technology has made significant advances in the last decade. To achieve the next step towards the deployment of truck platooning, an integral multi-brand approach is required. Aiming for Europe-wide deployment of platooning, 'multi-brand solutions are paramount. ENSEMBLE's ambition is to achieve pre-standards for interoperability between trucks, platoons, and logistics solution providers, speed up actual market pick-up of (sub)system development and implementation and enable harmonization of legal frameworks in the member states.

Project scope

The main goal of the ENSEMBLE project is to pave the way for the adoption of multi-brand truck platooning in Europe to improve fuel economy, traffic safety and throughput. This implementation of the technology has been demonstrated by driving up to seven differently branded trucks in one (or more) platoon(s) under natural world traffic conditions across national borders. Over the last 4 years, the project goals have been:

- Year 1: setting the specifications and developing a reference design.
- Year 2 and 3: implementing this reference design on the OEM own trucks, as well as performing impact assessments with several criteria.
- Year 4: focus on testing the multi-brand platoons on test tracks and public road.

Abstract of this Deliverable

In this deliverable, the impact of the ENSEMBLE multi-brand platoon on traffic flow is presented. The main idea is focused on assessing mechanical effects of multi-brand platoons on traffic flow, such as infrastructure capacity and other traffic indicator effects based on several factors inherent to the platoon such as the truck ratio, length, and manoeuvre execution by means of a traffic simulator. This document describes the methodology implemented for conducting the assessment, and details on the implementation of the "white-label" truck implementation (specified by WP2 and detailed in deliverables D2.3 and D2.5) within the traffic simulator integrated in this evaluation. This so-called white-label truck incorporates the minimal requirements, framework, and interfaces for multi-brand platooning, in that, it can serve as a model for forming, maintaining and dissolving platoons as well as handling a vehicle cut-in, considering traffic and infrastructure requirements and road sections where platooning is allowed.

To assess traffic impacts of multi-brand platooning, an evaluation method based on a combination of simulation approaches and open road testing is developed. Research question and key performance indicators (KPI) are defined for measuring the impact specifically around highway

discontinuities where congestion is recurrently triggered. Based on the research questions, simulation experiments are systematically designed and simulations with stochastic traffic flows are conducted to illustrate the aggregated effects of specific factors in mixed traffic or platoon operation. A data collection plan is also presented in this document providing recommendations to perform Open Road Testing of the multi-brand platoon. Data collected in these experiments is used to provide qualitative evaluation of impact of the platoon. The final contribution of this deliverable is to provide a general perspective on how multi-brand platoons can be studied and how to quantify their impacts on traffic. In the future, this can be used as a basis for creating real-time monitoring of the impact of truck platoons driving on roads under the mandate of road authorities in particular areas.

The findings suggest that truck platoons, as part of mixed traffic, are potentially able to increase road capacity and to postpone and mitigate traffic congestions. The effect depends on the ratio of truck platoons as part of the total traffic and the location in the network. The impacts of truck platoons on road capacity were found to be different between support and autonomous platooning due to the difference in distance between the trucks. Truck platoons with a smaller following gap show fewer improvements to road capacity than platoons with a larger following gap at a merging bottleneck. Road operators can take advantage of platooning trucks to increase their road capacity by applying temporal large following gaps near merging bottlenecks. The V2I communication possibility of platoons can be used to announce the presence of a platoon to the ramp-metering installations, such that these installations can adjust the traffic that is merging into the highway.

Chapter 1 gives a background overview, the aim and the structure of this report, and its relationship to the other work packages. Chapter 2 introduces the methodological approach that can be considered for assessing the impact of truck platoons in traffic flow. Chapter 3 presents the framework of simulation defined in ENSEMBLE based on the specifications of the white-label truck platooning layers. It also describes the modules of the tactical and operational layers as well as the V2V and V2I communication modules in a nutshell. The simulation framework presented here involves the deployment and availability for two different traffic microsimulation platforms. The first one is a commercial platform available in the market, and a second one is an open-source platform.

Chapter 4 introduces the experiments conducted during the open road testing, and the data collection procedure involved in the process to assess the impact on traffic flow. It is also important to highlight that one of the main contributions is focused on a software architecture for which documentation is available at https://ensemble-docs.readthedocs.io. General details of working principles are described in this deliverable.

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1. INTRODUCTION

1.1. Assessment of new Intelligent Transportation Systems

At the moment of writing this deliverable, Europe is the most urbanized continent in the world: Over 80% of its population lives in towns and cities (European Commission Directorate-General Environment 2004). Near 25% of total emissions for CO_2 generated by human activity are produced via transport activities. The number of circulating vehicles has increased dramatically and traffic congestion has become a major problem, not only from a safety point of view, but also from an economic and environmental perspective. However, along with increased congestion, recent years have also brought some promising improvements, particularly in the areas where ITS have been put into practice.

Since the development of the first Intelligent Transportation System (ITS), impact assessment of new technologies has been a key aspect to be measured. Connected Intelligent Transportation Systems (C-ITS) covers a large and wide range of new technologies that are deployed as part of Information Technology (IT) systems aiming to improve road safety, driver comfort, transport efficiency and conduct to refinements in secondary effects at environmental level as well as in energy management. Core technologies such as networking technologies, and advanced automated driving systems position the ITS in a new era of transportation. During the last decades, the deployment of sensors and data collection systems in traffic infrastructure has led to developments of C-ITS services in a partial stage. The development of new technologies transforms vehicles' role as they become information providers as well as participants of a traffic dynamics, therefore creating a synergy between information and transportation physical domain.

A range of evaluation studies have demonstrated sustainable impact of C-ITS systems in terms of economic, environmental, and societal aspects, when deployed in real scenarios. These evaluation results are not regularly accessible, and their design is focused on specific project goals. Different evaluation methods were used in the past years and important differences may emerge from the extension of these results into subsequent traffic situations. A key aspect for the deployment of new methods is the cross validation of a methodology along multiple projects. This emphasizes the development of the assessment methods in a generic way to address multiple objectives

Within the C-ITS domain, decision-makers seek good insights on specific tools that optimize the investment cost and the benefit of a particular solution, the impact in multiple sectors and the scalability of the proposed solutions. Researchers are committed to propose adequate approaches for ITS impact evaluation enabling comparison across different domains and different projects. Industry partners are interested to receive information related to the trends and key factors that foster ITS solutions and the best practices at the deployment level.

1.2. Truck Platooning and C-ITS services

Recent advances on truck automation have shown to be the promising future towards full automated driving. Moreover, new data sources like mobile sensors and connected vehicles have revolutionized traffic management. Current probe data generated by vehicles deliver current position, motion, and time stamp. Equipped trucks will enrich vehicle data with additional attributes such as headway, traction information, brake status, hard braking, activation of emergency lights, anti-lock brake status, airbag deployment status, windshield wiper status, etc. Fusion of heterogeneous data sources bring more information to complete information. Moreover, the combination of simulated data and experimental data enriches the analysis and may extend the diagnostic results of multi-brand platooning. Wireless communication technologies can be utilized to generate real-time probe-data that can help to improve estimation and detection of traffic conditions, for example queue-end detection algorithms. Options to improve include vehicle-tailored and location-based recommendations or guidance through I2V communication. Multi-brand platooning enables drivers' decisions to be tailored to real-time traffic conditions acquired via information communicated directly to the vehicle.

The ENSEMBLE project paves the way into the development of these new technologies by bringing truck platooning to a multi-brand framework, which is feasible and deployable. Inherently, platooning technologies have a number of consequences on traffic and the environment, and these impacts need to be evaluated at different levels in terms of a C-ITS service. Initial aspects may consider, for instance, the type of service under creation and its impact on traffic flow. The main incentives to conduct traffic flow impact assessment can be established from the point of the following aspects.

Infrastructure management incentives

By taking the routing and vehicle clustering aspects specifically into account in the Strategic Layer, implementation of efficiency improvement of road capacity can be made explicit. Road infrastructure may benefit from platooning by increased capacity through shorter following distances. This capacity increase is achieved by up to 46% reduction in area claim of the truck convoy when they drive at a very short distance, e.g. 0.3 sec (Alam et al. 2015). In terms of road infrastructure usage transformation, the appearance of new approaches may motivate the implantation of platooning technologies. For instance, the use of dedicated truck platooning lanes with long platoons of up to 10 trucks could yield more than a doubling of capacity (Tsugawa, Jeschke, and Shladover 2016). They have investigated multiple different combinations of truck platoon size, following distance and speed. They found that even with two or three vehicle truck platoons, capacity gains could be achieved of up to 25% on a dedicated lane. A main prerequisite of a theoretical capacity gain from truck platooning comes with the condition that the gaps during platooning must be maintained over a significant distance and time.

Traffic flow incentives

Vehicle platoons have an impact on traffic flow improvement by damping out traffic (braking) disturbances that may even lead to traffic jams. Truck platoons have also been found to potentially improve traffic flow through increasing overall traffic homogeneity (Ramezani et al. 2018). Multiple layer control architectures aid in the improvement of traffic throughput with an increasing homogeneity (Duret, Wang, and Ladino 2020). Published studies have found improvements in flow of nearly 10% for penetration rates of 30% of the vehicle population, and these increased quadratically with the penetration rate (Milanés and Shladover 2014). Using traffic simulation tools, ENSEMBLE validates the impact of platooning on traffic, using improved automated vehicle models and algorithms. More advanced strategies aim to provide information about speed homogeneity and flow stability.

Environmental incentives

Climate change is an important concern in the world nowadays. Green-house emissions originating from transportation are one of the main targets to be reduced. The large, expected increase in road freight transport due to the increase of e-commerce and the development of urban centres presents great challenges with respect to energy consumption and emissions. Many industrialized countries agreed to reduce greenhouse gas emissions under the Kyoto protocol, the Paris agreement and the COP26 (Joselow 2021). In addition to this agreement, the European Union has set more ambitious targets and aims to reduce emissions by 80–90% by 2050 with respect to 1990 levels. This requires a 60% reduction (or 70% with respect to 2008 levels) in green- house gas emissions from the transportation sector (European Comission 2016). Improving the efficiency of the current freight transportation system is a challenging and complex problem.

A potential solution is found in multi-brand truck platooning. At first sight the technologies developed in the ENSEMBLE project aim to target a generic and cross platform solution which works for multiple truck manufacturers. This aspect is important factor for the adoption of new technological solution as providing standardisation reduces the friction and motivates new markets and business models. Experimental results exhibited in (Alam et al. 2015) list the average fuel and energy savings for a three-vehicle platoon traveling over road segments with small road grade. Potential benefits on a mono brand setting vary in between 4.5% and 7.5% in terms of energy consumption. This benefit can be translated into emission reduction as detailed in (Treiber and Kesting 2013).

1.3. Aim of this report

Concerning the future of Europe's freight transport, there are several challenges to be taken up to remain sustainable in environmental, economic, and societal sense in terms of decarbonisation, greater efficiency, and competitiveness. The expected impact is on a Europe wide deployment of platooning with multi-brand vehicles in real, mixed traffic conditions. It is the explicit aim of this project to take the last steps of technological research before deployment of multi-brand truck platooning. Assessing truck platooning technologies in terms of traffic comprises multiple layers of evaluation.

This deliverable aims to provide all the material for replicating a multi-brand platooning strategy (MPS) in a microscopic traffic simulation environment. Interactions between truck platoons and other traffic participants have been captured, supporting modelling the heterogeneous interactions between existing traffic models and the intended behaviour of the multi-brand platoons embedded in traffic. For this purpose, a software interface is implemented, and it employs definitions of a tactical control layer, and operational control layers that have been developed in WP2 and WP3. In addition, deployment of high precision traffic sensors, combined with high-level V2X communication, and control algorithms make it possible to implement deployment and validation of truck platoons in real-world traffic. The sources on design which have been used in this task are directly taken from the outcomes of WP2:

- D2.3 Platooning use-cases, scenario definition and Platooning Levels (Willemsen, 2022),
- D2.5. Functional specification for white-label truck. Provides use cases, situations that can be used as reference for testing (Mascalchi E., 2022).

Specific components tied to the behaviour of the control of the trucks at individual level are entirely described in the MPS. This involves the way simulations are executed, the way platoons can be parametrized and how that impact can be measured with specific key performance indicators. All the materials from these work packages served as an input to adapt a simulation framework which is generic to various traffic simulation platforms. Particularly, in the case of the project, interfaces for the microscopic simulators, Vissim[1] and SymuVia[2], have been deployed and tested via preliminary tests performed to verify the generic specifications. Data collected at the Open Road testing may serve in determining real impact of platoons on the roads and verify the interaction of other road users with truck platoons.

1.4. Multi-brand Platooning Strategy

The introduction of integral highway traffic automation creates business opportunities for service providers on the traffic flow automation layer (e.g., ADAS systems for connected and autonomous vehicles). In addition, the automotive supplier sector will be able to extend their product range with communication devices, while increasing sales of on-board sensors such as radar and camera. The functionalities of truck platooning can be classified in three levels when referring to traffic flow:

[1] Vissim is a commercial platform simulator developed by PVT Group and used by TNO. See more information at https://www.ptvgroup.com/en/solutions/products/ptv-Vissim/

[2] SymuVia is an open-source microscopic dynamic traffic simulator developed by UGE. See more information at https://github.com/licit-lab/Open-SymuVia

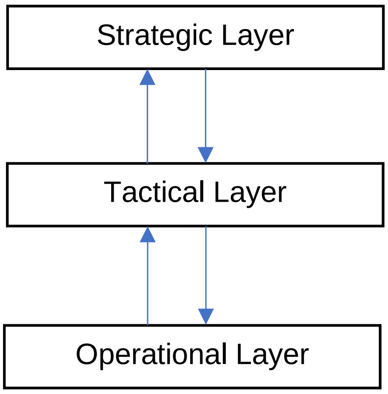


Figure 1. Main scheme for the ENSEMBLE multi-brand platoon system architecture

Strategic layer effects

The strategic layer is responsible for the high-level decision-making regarding the scheduling of platoons based on vehicle compatibility and Platooning Level (see D2.5), optimization with respect to fuel consumption, travel times, destination, and impact on highway traffic flow and infrastructure, employing cooperative ITS cloud-based solutions. In addition, the routing of vehicles to allow for platoon forming is included in this layer. The strategic layer is implemented in a centralized fashion in so-called traffic control centres. Long-range wireless communication by existing cellular technology is used between a traffic control centre and vehicles/platoons and their drivers.

The potential impact on the strategic level may conceive aspects related to the improved rerouting of platoons to increase efficiency of the infrastructure. While it is not within the scope of the present work, these effects could be an interesting topic for future investigation.

Tactical layer effects

The tactical layer coordinates the actual platoon forming (both from the tail of the platoon and through merging of platoons) and platoon dissolution. In addition, this layer ensures platoon cohesion on hilly roads, and sets the desired platoon speed, inter-vehicle distances (e.g., to prevent damaging bridges) and lateral offsets to mitigate road wear. This is implemented through the execution of an interaction protocol using the short-range wireless inter-vehicle communication (i.e. V2X). In fact, the interaction protocol is implemented by message sequences, initiating the manoeuvres that are necessary to form a platoon, to merge into it, or to dissolve it, also considering scheduling requirements due to vehicle compatibility.

Operational layer effects

The operational layer involves the vehicle actuator control (e.g. accelerating/braking, steering), the execution of the aforementioned manoeuvres, and the control of the individual vehicles in the platoon to automatically perform the platooning task. Here, the main control task is to regulate the inter-vehicle distance or speed and, depending on the Platooning Level, the lateral position relative to the lane or to the preceding vehicle. Key performance requirements for this layer are vehicle- following behaviour and (longitudinal and lateral) string stability of the platoon, where the latter is a necessary requirement to achieve a stable traffic flow and to achieve scalability with respect to platoon length; the short-range wireless inter-vehicle communication is the key enabling technology.

1.5. Potential preconceived impact – Key Performance Indicators

Truck platooning has the potential to improve road safety and increase traffic efficiency. Impact of truck platooning on traffic flow can be measured via real-world road tests that capture data about the platoon state and the traffic state when the platoon appears. These effects are expected to be measured by focusing attention on three main aspects:

Dynamic Performance and Operation: *Measure dynamic characterization of a multi-brand platoon formation* is important for this purpose. The main objective here is to quantify the stability of the time and space headways, and acceleration profiles for specific maneuvers and within determined trips. Quantification of the variation of these variables can impact the stability of traffic flow regimes, during steady flow conditions. The dynamic performance also includes behaviors on the formation, the creation and the dissolution.

Impact on traffic flow & other road users: The existence of platoons in traffic inherently causes changes in behavior of traffic surrounding the platoon. Drivers approaching a platoon may tend to keep safer distances, overtake under specific conditions, or simply modify their driving speed. Being able to capture specific traffic indicators related to the presence of platoons may help to quantify this behavior.

Platoon behavior during maneuvers: Given the different levels of platoon specifications, determining the impact of specific platoon maneuvers performed under the presence of several traffic conditions is important to assess the impact of truck platoons on traffic flow. Truck platoon maneuvers such as: joining a platoon, dissolving an existing platoon, real cut-in maneuvers from external drivers can be characterized in time and space, and they can provide insight on how the deployment of such strategies may lead to an effect on traffic flow.

1.6. Structure of this report

This report aims to provide all the material for replicating a multi-brand platooning strategy (MPS) in a microscopic traffic simulation. It will employ the tactical layer algorithms that have been developed in D2.3 (Willemsen, 2022) and D2.5 (Mascalchi E., 2022). In addition, simplified vehicle and sensor models, a high-level V2X communication model, and operational-layer control algorithms will be implemented, which have been used in WP2 for specification purposes. These components together entirely describe the MPS as it has been implemented by the OEMs in the ENSEMBLE project. All the material will be adapted to and implemented in a traffic simulation tool and preliminary tests will be performed to verify the generic specifications.

The ENSEMBLE project aims to test multi-brand platooning strategies by implementation in a realistic traffic scenario. It has been tested on a highway section with a merging on-ramp, which is a typical location for causing bottlenecks through periodic congestions on highway corridors. Performance Indicators (PI) have been defined for evaluating the impact of multi-brand platooning, specifically around discontinuities where congestion may be triggered. Different traffic scenarios have been executed, and the resulting PIs have been analysed. The results show that, under certain conditions, truck platooning is effective in reducing or removing congestion and improving safety, especially among cars. Some future directions have also been proposed on how to further optimize the impacts of multi-brand truck platoons.

The next chapter introduces the methodological approach that can be considered for assessing the impact of truck platoons in traffic flow. Subsequent chapter presents the framework of simulation defined in ENSEMBLE based on the specifications of the white-label truck platooning layers. It also describes the modules of the tactical and operational layers as well as the V2V and V2I communication modules in a nutshell. The next chapter introduces the experiments conducted during the open road testing, and the data collection procedure involved in the process to assess the impact on traffic flow. The main conclusions and future directions from the deliverable are highlighted in the final chapter of this deliverable.

2. METHODOLOGY FOR ASSESSMENT

2.1. Evaluation of C-ITS Systems

Since the development of the first Intelligent transport system (ITS), impact assessment of new technologies has been a key aspect to be measured. Cooperative intelligent transport systems (C-ITS) cover a large and wide range of new technologies that are deployed as part of Information technology (IT) systems aiming to improve road safety, driver comfort, transport efficiency and conduct to refinements in secondary effects at environmental level as well as in energy management. Core technologies position the ITS in a new era of transportation, and ENSEMBLE platooning function is one of them. During the last decades the deployment of sensors and data collection systems in traffic infrastructures has led to developments of C-ITS services in a partial stage. The development of new technologies transforms vehicles' role as they become information providers as well as participants of a traffic dynamics, therefore creating a synergy between information and transportation physical domain. A range of evaluation studies have demonstrated sustainable impact of C-ITS systems when deployed in real scenarios in terms of economic, environmental and societal aspects.

2.1.1. Motivation for a methodical approach in ENSEMBLE

As signalized by (Lu 2016), from the departure point and development of C-ITSs, multiple approaches have been suggested to assess the impact and the implementations. Multiple frameworks have been deployed, see (FoT NET 2018; William Stockton et al. 2003) and some positive points have shown the advantage of implementing C-ITS services as part of new solutions for transport systems. The platooning case has been tested previously in several situations as detailed in (Alam et al. 2015). Recently, the European Truck Platooning challenge benefits in a mono brand setting showed (Aarts and Feddes 2016). However, some issues are still encountered while performing the assessment process. The same issues seem to be existent in several cases:

1. Evaluation results are often not systematically structured.
2. Results are conducted for specific cases and validation of them is limited to certain settings that are difficult to exploit in other scenarios.
3. Comparison efforts for the same evaluation strategy among different projects are difficult to find.
4. Impact evaluation is regularly limited to Field Operational Tests (FOTs), and scalability of the proposed solution is examined for very specific cases.

The objective of the here proposed methodology is to reduce this gap and establish a general framework that works towards the generic evaluation of C-ITS services. In order to do that, the methodology relies on inputs from the project, in particular WP2 for the ENSEMBLE project (the specifications of the platooning system) as key elements to design the evaluation procedures, objectives to be setup and measured, as well as the design of Key Performance Indicators (KPIs) resulting from the implementation process.

2.1.2. Aim of the methodology

The framework provided in this document is not intended to prescribe a specific guide step by step, but rather to serve as a generic guidance document to conduct the impact assessment of truck platooning on traffic flow efficiency. Some key aspects that constitute key aspects for the development of this methodology are:

1. Contribute to the project management, risk evaluation and impact assessment for the deployment of ENSEMBLE multi-brand platooning in particular in orientation towards the Open Road Tests conducted in the project.

2. Conduct a review of existing frameworks and assess their value and relationship with the current existing policy objectives.

3. Develop a specific methodology suitable for different stakeholders involved in the deployment of platooning. Potential users of the assessment procedure are Project Partners, Traffic Authorities, Researchers.

4. Provide general guidance and assist the stakeholders in the assessment of evaluation preparatory actions for future deployments of truck platooning by instantiating a guide of best practices on deployment.

5. Incorporate evaluation specific procedures as part of the methodology if they are required.

2.2. Orientation of the methodological approach

Different evaluation strategies have been developed for the assessment of truck platooning strategies. In this case we summarize the two main strategies followed here, and the way they should be selected.

2.2.1. Objective-based strategy

In the most generic sense this set of strategies is oriented to achieve certain performance levels, goals or objectives in the evaluation process. The main idea is to measure the progress or contribution of a system to those specific goals. In the case of Platooning in ENSEMBLE, it can be oriented in terms of how the introduction of a particular service contributes to the general performance of a traffic factor measured as a consequence of this service. For example, this strategy can be useful to identify what kind of platoon function deployment is optimal for different traffic and road environments.

2.2.2. Criteria-based strategy

In this case, explicit criteria should be issued as a point of reference for the evaluation. The difference with the objective-based strategy is that the criteria are not focused on the organizational content but rather in a more general goal for the ENSEMBLE multi-brand platooning. This, for example, can be good as part of a field test project in which the intention of evaluation is focused on the interoperability of the solution, the validity of a specific use-case with respect to the implemented technology under specific scenarios. This can be seen as a superset of goals that is more transversal. For example, several criteria can be identified like extending the ODD (operational design domain) to operate across European borders, guaranteeing the interoperability of the solution among different brands, etc.

2.3. Definition of Assessment Methodology

The main key in the definition of the assessment methodology for impact assessment is to describe what is to be learned and expected from the ENSEMBLE project, and what is to be achieved by testing the application. It is also important to provide a complete and integral impact assessment in a defined window of time, meaning that the evaluation period itself can be treated as a subproject in the main project. Evaluation objectives should be determined on the basis of:

- The real-world problem characteristics,
- The particular needs to be covered with the implementation of the technology,
- The risks that the implementation could bring at a technical level or at the moment of usage.

The definition of the objectives can also help to classify the type of impact that is under study, for example direct and indirect impacts. Direct impacts (e.g., improved speeds) are generated by immediate deployment of the platooning service, while indirect (e.g., benefits for non-users due to the improved system efficiency) are a consequence of direct impacts. Direct impacts have significant effects in the short run while indirect impacts affect the system and the aspects under study in the longer term. Longer term impacts are important and should not be neglected as they constitute important measurements and features of the C-ITS solutions bringing along cost effectiveness. Moreover, some indirect impacts can also yield benefits in the short-term, for example, non-users following truck platoons might experience less traffic disturbances and less variance of acceleration.

Two strategies can be followed for the assessment depending on the required viewpoint of the assessment:

Platooning as a system

In this strategy the main purpose is focused explicitly on the users. The evaluation should have full knowledge of the system since the assessment results will depend on the correct operation. An example of this assessment leads merely to some technical operation of devices or specified tasks to be executed by a particular platooning service. The present deliverable is focused on the user perspective and, hence, we consider the platooning as a system in this case.

Platooning as a service

For this case, evaluation is conducted towards an observation of certain conditions in a predefined situation. In this case, the system is part of an environment and the impact of a functionality considering certain use cases can be measured. Regarding this approach, interviews with users are necessary, but data collection becomes significantly easier. Performance evaluation requires the analysis of a particular achievement, the qualification in terms of benefit should be defined within the specific use case, and regularly observed via a key performance indicator.

2.4. Methodological Approach

2.4.1. Approach

The deployment of connected vehicle technologies is in the agenda of many European projects, up to date some strategies have been proposed in order to describe comprehensive connected vehicle methodologies freely available to support assessment studies. The proposed methodology can be explained in the context as seen in Figure 2.

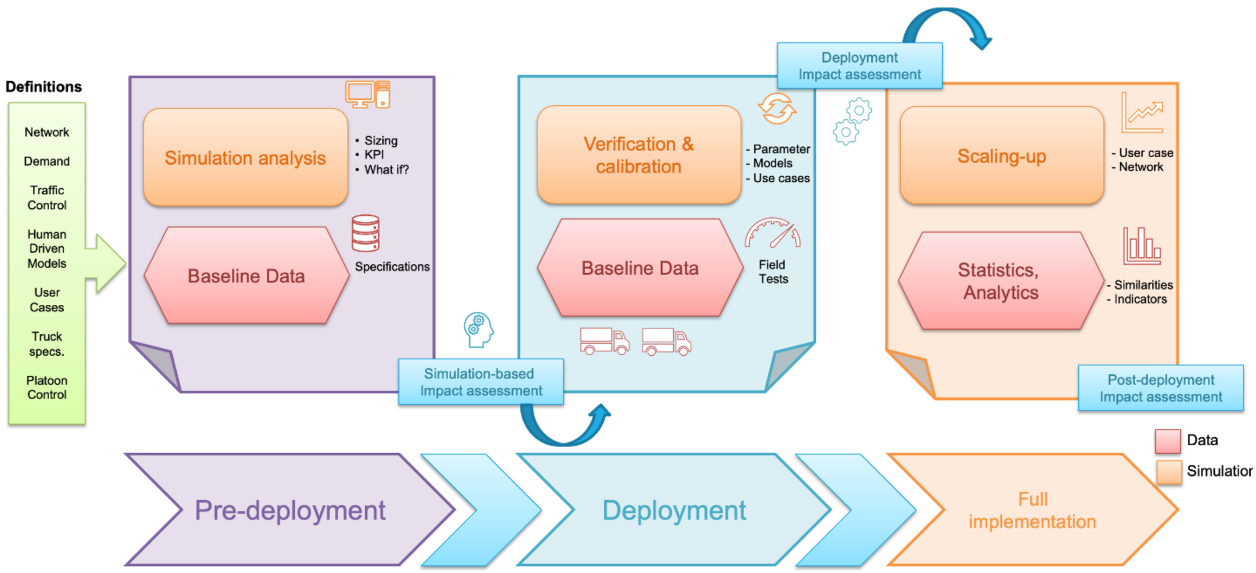


Figure 2 Methodology for assessment used in ENSEMBLE

The first requirement to be able to perform the impact assessment is the precise definition of the traffic network, a pre-defined demand for the network, and pre-established configuration for elements of control in the traffic network such as specific control policies or speed control policies. After this, three main phases of development are conceived:

- The first phase comprises a simulation analysis, meaning that it is necessary to integrate features/models for performing the assessment related to the KPIs.
- A second phase is a phase of iteration and calibration, meaning that once the modeling part has been initially tested, use-cases can be configured, and initial comparisons can be made on the behavior of the system. Data from an FOT can be retrieved and used for the calibration phase.
- Finally, a third phase can be imagined where all the experiences of the FOT are utilized enabling simulation tools to scale up for a wider road network and future scenarios.

The calibrated model generates an expected impact denoted baseline gathering the full simulation environment description necessary to reproduce traffic conditions for the traffic network under analysis. Parameters for this calibration can be established by an expert and they should be verified via baseline data obtained from the initial scenario. The traffic scenario jointly with the use case scenario defines the implementation of a specific platooning functionality service which can be implemented and measured via KPIs. The latter defines a collection of indicators from the traffic network that can be measured directly or estimated from data collected in a simulated or experimental test. The procedure for evaluation involves then in a first stage an assessment of impact at simulation scale. This stage aims to determine the efficiency of the platooning functionality by means of information extracted from simulated data. A first checkpoint in the evaluation is established at this point by measuring KPIs over the virtual environment. Information collected via KPIs is essential for the definition of FOT characteristics, such as guidelines for data acquisition procedures, sensor specifications, synchronization, guidelines for database and IT infrastructure implementation as well as adaptation on several guidelines for the field tests. The deployment of conditions studied at simulation level then, in reality, produce experimental data characterizing an impact after deployment (last stage in Figure 2 collecting information from field experimental tests guided by (FESTA methodology — See Sec.2.2.3)). The assessment methodology for the multi-brand platooning functionality is proposed in the two phases that involve impact assessment estimated and established from simulation scenarios as well as well as impact measured from data obtained in specific defined scenarios.

2.4.2. A set of good practices

In summary, a set of good practices is provided below, some similarities may be found with the methodology FESTA proposed in (FoT NET 2018). In this case some of the best practices involve procedures that are described in the subsequent chapters:

Selection and description of functionalities.

Regularly, it is quite clear from the beginning what functions or at least what type of functions in the platooning functionality will be the object of study. The needs of the different stakeholders need to be identified and merged into a common requirements description. In addition, other specifications should be given for the functionality, for example, boundary conditions should describe where and under what circumstances the system/function will operate according to its specifications, technology specifications, infrastructure requirements, identification of functionalities under specific conditions such as geography and demography constitute a good practice.

Definition of use cases.

In general, this input is provided by the project objective itself, and it can be oriented specifically to a single project or executed for multiple ones. Use cases can be classified in terms of events, situations or scenarios. In case of users, the interaction between the user and the system creates a set of transactions that can be recorded. In the case of situations, the target is focused on modifying specific conditions for the study, these situations can be recorded in specific defined variables containing the specific situation. Situations may include parameters such as vehicle specifications, environmental conditions, driver characteristics or states. These specific situations can be specifically defined as in (FoT NET 2018) [sect. 4.8].

Creation of hypothesis and questions.

The research questions specific to the assessment of a particular platooning functionality can only be identified once the overall goal of the service and its interaction with the use case has been established. The hypothesis creation involves multiple aspects, these can be detailed in a set of generalities to be accounted such as the level of system usage e.g., purpose of journeys when the particular platooning functionality is used, the impact of system usage e.g., risk of accident, impact on individual driving behavior, impact on the traffic efficiency, environmental impact. The hypothesis also needs to consider the elements described for the objective formulation meaning the type of analysis, functionality, relevance of the service, etc.

Approaches for the solution of the questions.

Once the particular hypothesis and corresponding research questions have been formulated, it is important to identify the way this hypothesis is going to be tested. The approach could involve an approach from a generic case to a specific case e.g., analysis of traffic improvement from a macroscopic scale towards a microscopic scale. A second approach could analyze the hypothesis starting from the direct effects of deploying the platooning functionality towards the impact on other conditions e.g., analyzing the impact of platoon length in time reaction of a driver or the effects on external drivers or nearby areas where the situation occurred. A final approach to solve the question is from a hierarchical point of view, where hierarchy is regularly established by the hypothesis itself.

Experimental design.

This reflects in summary the type of tests executed in an experimental environment that contributes to the evaluation of impact. The definition of the FOTs can be included in a larger sense as explained in (FoT NET 2018). In that case the reference is focused on all types of actions that involve the evaluation itself. In this case the FOT is referred to be the process of designing and deploying an experimental design, specially conceived for the evaluation of the platooning functionality. Experimental design can be of a different nature, one key important element is to consider the control case as part of the design. This can be included as part of the baseline for the raw data collection.

An important question to be answered within the experimental design is the characteristic of the experiment itself: an experiment can collect and produce data for a specific aspect of interest e.g., monitoring speed variations for a specific situation or it can be designed so that the experimental condition retrieves data at multiple levels such as energy indicators in conditions of speed variations due to notifications of a specific platooning condition that has been activated. In the former one the scope of the experiment is short and precise while in the second it implies the collection of several variables.

Supplementary tools

Supplementary tools refer to software, surveys, and data preprocessing that complement experimental design in order to test the predefined hypothesis. In a larger sense this means a collection of tools to guarantee the correct execution of a FOT. For instance, definitions on how data is collected, how privacy is preserved according, required simulations to recreate specific conditions partially observed with data collected of the experiment are part of this supplementary tools. In some cases, a formal study is required to provide incomes to the experimental setup.

Formulation of impact in terms of KPIs.

During the process of developing hypotheses, it is important to choose appropriate Key performance indicators (KPIs) that will allow answering the hypotheses, but that will also be obtainable within the budget and other limitations of the project. Many different kinds of KPIs have been used in previous studies and are related to various aspects of driving. Performance indicators are quantitative or qualitative indicators, derived from one or several measures, agreed on beforehand, expressed as a percentage, index, rate, or other value, which are monitored at regular or irregular intervals and can be compared to one or more criteria. Iteration is especially important when defining research questions and hypotheses, because usually a selection has to be made from a large number of possible hypotheses, based both on their relation to the main impact areas and research questions and on practical issues. Another important iteration point is the impact areas. The final question of the impact assessment may drive the design of the platooning evaluation in all its aspects. When practical issues, such as which data-loggers to use, make certain choices hard to realize, iteration to earlier stages is necessary.

Scale up.

Evaluation of the full performance of a specific technique is important sometimes, it is not simple given that costs would explode, and regularly adoption of the technology is at an early stage. Getting a representative sample of the whole population is impossible. However, it is acceptable to have an imperfect sample, as long as the limitations of the sample are known and they are described in the end results. Two general distinctions can be established for the scale up. The first one is linked to statistical methods based on data-based approaches: in this case the information compiled from the FOTs is collected and its statistical information is used in order to project hypothetical situations. Scaling up using statistics is applicable when interaction and second-order effects are not relevant. A second approach is making use of simulation tools in order to account for the impact of the specific platooning functionality on determined situations. Scaling up using a traffic model is a good method to apply when second-order effects are expected and/or when the effects of the platoon can be used directly as an input parameter for the traffic model.

2.5. Application in the ENSEMBLE Project

Given the aforementioned research scope and methodology, specific research questions and key performance indicators are defined for the impact assessment of multi-brand truck platooning in the ENSEMBLE project. Project goals are converted to research questions, and they will be answered by the quantitative analysis of key performance indicators.

2.5.1. Research questions

The aim of impact assessment in the ENSEMBLE project about multi-brand truck platooning is to investigate the effects of truck platoon operation on traffic flow performance such as road capacity, congestion formation and travel time. This impact assessment focuses on the efficiency of traffic flow operation as well as on the travel time benefits for the end-users of the ENSEMBLE truck platooning service. The main research is formulated as:

What are the impacts of multi-brand truck platooning operation on traffic flow performance?

The operational design and system setup of a multi-brand truck platoon largely determines how a truck platoon interacts with other traffic participants and therefore plays an important role in the platoon's impact on traffic flow. The main platoon operational setup to be investigated within this impact assessment is the following time gap at different platooning levels. Truck ratios in mixed traffic and the level of the road network (network discontinuity and traffic corridor) are also considered as simulation variables to represent various traffic scenarios. Substitute research questions are described below:

- *What are the impacts of multi-brand truck platooning at a merging bottleneck?*
- *What are the impacts of platooning levels on traffic flow performance?*
- *At which level of truck ratio will the multi-brand truck platooning show significant improvement on traffic flow performance?*

2.5.2. Traffic flow performance Indicators

Traffic flow performance can be characterized by many indicators such as average speed, throughput, density, etc. Among them, indicators that have the potential to capture the influences of multi-brand truck platooning are selected as key performance indicators in this impact assessment research.

The existence of a truck platoon might place an influence on the throughput due to the shortened following gaps and improved traffic flow stability enabled by truck platooning. Given the coordinated manoeuvres within truck platoons, traffic disturbance will not be amplified and therefore congestion will expectedly not propagate to upstream sections.

Road Capacity/Maximum Throughput
The road capacity or maximum throughput describes the efficiency of vehicles passing a particular location/network. It is an hourly throughput estimated by the maximum vehicle counts within a time window of 15 minutes.

Queue Discharge Rate
The queue discharge rate, measuring the maximum throughput at the downstream segments after congestion takes place, reveals the efficiency of a vehicle passing traffic congestion. It is the hourly throughput estimated by the maximum vehicle counts measured at the downstream segments 1.5 km away from where traffic congestion happens. Queue discharge rate may be influenced by the level of traffic disturbances and traffic congestions.

Capacity drop
The capacity drop is the throughput reduction after traffic congestion takes place. It is often calculated/measured as the difference between road capacity and queue discharge rate, expressed in the number of vehicles per hour or normalized to a percentage.

Congestion pattern
A traffic congestion pattern refers to the formation and evolution of traffic congestions. It pays attention to the start time and location of the traffic congestion, if the congestion remains at a fixed bottleneck or if a moving jam that propagates to upstream sections, the severity of the congestion, as well as the congestion dissolution. The traffic congestion pattern is generally identified by the spatial-temporal plot of flow and speeds, which are measured by (simulated) loop detectors at fixed locations within a certain time interval. Traffic congestion pattern based on a spatial-temporal structure provides a straightforward illustration of how traffic flow operates on a road network within a time period.

Average travel speed per vehicle type
Travelling speed describes the overall travelling efficiency from the perspective of an individual vehicle trip. The average speed per vehicle type can describe the flow features specifically aggregated over a vehicle type. The comparisons of average speed between different vehicle types will distinguish the diverse impacts of the evaluated platooning system. The average speed is highly correlated to travel time. The larger the travel time, the lower the travelling speed. Average speed is preferred over average travel time as a performance indicator because the latter largely depends on the size of the evaluated network or the trip length.

Average travel time delay
Travel time delay is an indicator for drivers to perceive how much extra time will be spent against their expectations. Travel time delay takes the difference between the desired travel time and actual travel time for an individual trip. The desired travel time is estimated by the trip length over the desired travelling speed, while the actual travel time is the time measurement of a vehicle taking the

same trip (in simulations). Travel time delay will be small (close to zero) when traffic is freely operated and the delay will increase dramatically as traffic congestion appears.

Number of vehicle stops per vehicle

Given that vehicles lose time in the deceleration and acceleration phases before and after a full stop, the number of vehicle stops becomes an indicator to measure the flow efficiency, especially to depict traffic flow instability and as indicator for emissions. In this research, a vehicle stop is defined as the occurrence of a vehicle speed below 5 km/h for at least 5 seconds. In unstable traffic conditions such as stop-and-go traffic, vehicles encounter multiple stops during the trip and the number of vehicle stop per vehicle increases substantially.

Number of hard brakes per vehicle

The number of hard brake events is a traffic safety indicator since it is often triggered by safety-risk conditions, and it is an indicator for traffic flow stability due to the consequences of hard braking for creating additional disturbances. An acceleration below -3.5 m/s^2 for at least one time step is considered as a hard brake event in this evaluation research.

3. SIMULATOR SETUP

3.1. Truck Platooning

Simulation-based traffic impact assessment studies of advanced technologies such as truck platooning need to be carried out to ascertain their benefits for traffic efficiency, safety and environment. To reduce uncertainty in the results of such simulation-based studies, the same simulation studies can be performed in different simulation software. Many traffic simulation software packages (Aimsun, SymuVia, Vissim, SUMO) are currently available for traffic impact assessment of new technologies such as truck platooning. However, to fully model and simulate the functionalities of such advanced technologies in different simulation environments, several extensions need to be made to the simulation platforms. In most cases, these extensions have to be programmed in different programming languages (C++, Python) and each simulator has its own simulator specific user interface (API). This makes it difficult to reuse software written for a specific functionality in one simulation platform in a different simulation platform. To overcome this issue, this report presents a novel architecture for cross-platform simulation. The architecture is designed such that a specific functionality such as truck platooning or any other functionality is made platform independent. We designed a cross-platform architecture for simulating a truck platooning functionality using Vissim and SymuVia simulation software to determine the traffic flow effects of multi-brand truck platooning in the context of the EU project ENSEMBLE. In this section, we present the structure of the framework. The simulation framework is then applied to evaluate the traffic flow impacts of multi-brand truck platoons on a highway corridor with a merging bottleneck.

3.2. Review on Simulation Platforms

3.2.1. Truck Platooning

Improvements and impacts introduced by truck platooning are assessed as part of the project by considering several aspects such as road infrastructure, economic and environmental benefits, behaviour of truck drivers and other road users and finally traffic flow. Special focus is assigned to the yet-unexplored multi-brand case where the impact assessment is particularly challenging due to the heterogeneity in truck characteristics i.e., different loads, different braking capabilities and the use of unknown (‘black box’) platooning algorithms (these are usually kept confidential by each brand), which makes it more difficult to ensure platoon stability.

Some former works have presented traffic impact of platoons in highway traffic operations and traffic flow. In (Kunze et al. 2009), initial definitions have been provided in order to deploy platooning operations in regular highways. Effects of such implementations were studied in (Calvert, Schakel, and van Lint 2017), where it was found that potential effects of automated technologies may be observed only for high penetration rates. (Cicic and Johansson 2019b; 2019a) have detailed and exploited macroscopic models to explain the moving bottleneck effects that platoons may induce in traffic flow. Although these models are of high computing efficiency, specific effects regarding vehicle interactions that are not defined for such models may produce instabilities . (Calvert, Schakel, and van Arem 2019) performed detailed impact traffic assessment by developing quantitative proof of the potential effects of truck platooning on traffic flow performance. The results showed that truck platooning may have a small negative effect on the total non-saturated traffic flow, however with a much larger negative effect on saturated traffic flow. More recently (Jin et al. 2020) proposed tandem-link fluid models that consider randomly arriving platoons sharing highways with regular vehicles by defining control architectures and their impacts in such situations. These works have settled an initial base that considers platoon specifications complementary to the ENSEMBLE project. In our case, the multi-brand heterogeneous factor and a detailed hierarchical logical layer have been designed to model accurate interactions between platoons and regular traffic.

3.2.2. Framework of two connected simulators

The proposed application is designed as a command line interface where commands are interpreted and then transmitted towards traffic simulators via a standard socket communication scheme. A scheme of the full framework can be found in Figure 7. In order to connect both traffic simulators we consider SymuVia and Vissim via a Shared Library[3] in the former case and a port communication in the later one. The main objective of these sockets is to transmit information and commands towards the corresponding platform such that the dynamic of the full traffic is evolved according to the platoon definitions.

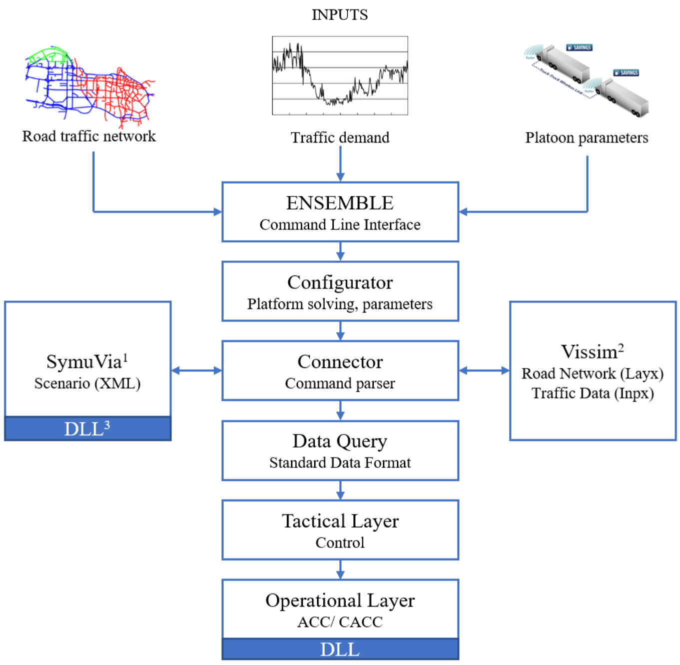


Figure 3. Proposed cross-platform framework to emulate truck platoons in connection with traffic simulators

[3] Shared Libraries are compiled binary files. Dynamic Link Library (DLL) corresponds to a specific implementation of such binary files for Microsoft ® platforms.

Figure 3 illustrates the general workflow of information starting from the input to the system until it reaches the specific automated vehicles. The application receives three main data inputs namely, a representation of the traffic network (XML for SymuVia, LAYX for Vissim); information regarding the traffic behaviour, in particular, traffic demand for the incoming nodes; and finally, a parametrization of the platoon in terms of vehicle generation and origin destination matrices.
The application processes the data via a configurator, which is in charge of verifying the integrity of the input data and afterwards it starts the evolution of the full traffic simulator by enabling the corresponding platforms and connectors. A standard data format is used to describe vehicle information and software patterns are used for the implementation of such blocks to guarantee efficiency and data integrity protocols in the general framework. Traffic state is pulled from the simulator via a data query function which then is sent to the tactical layer. This block considers specific vehicle types to define platoons in the simulation and assign the corresponding behaviour at macro level. Tactical decisions involve general manoeuvres like platoon splits, reaction to cut-ins, or commencement of a formation.

3.2.3. Tactical layer

The ENSEMBLE project has considered the platooning function as a support functionality for drivers at a longitudinal level. General manoeuvres are considered in use cases handled by a state machine in charge of determining low level information that should be transmitted to each of the trucks. The objective of the tactical layer is to provide an interface to build up the communication layer that will send information through the whole platoon. Two main streams are considered: first, the rear gap coordinator collects platoon information of the ego truck and information upstream of this vehicle such as the maximum length of the platoon, and the position in the platoon. The second stream receives data downstream of the ego truck and collects information related to platoon vehicles downstream of the ego truck, in particular information about the immediate leader. These two blocks determine the ego truck state which can be classified as a discrete set (StandAlone, Joining, Platooning, FrontSplit, BackSplit, Cut-in) defining steady state or transition actions the operational control should perform for the current ego truck (see Figure 4). Once the state is determined, specific transitions are defined among those states via a logic state machine. This design aims to ensure safety in the manoeuvring as well as smooth dynamic transitions operated by the operational layer.

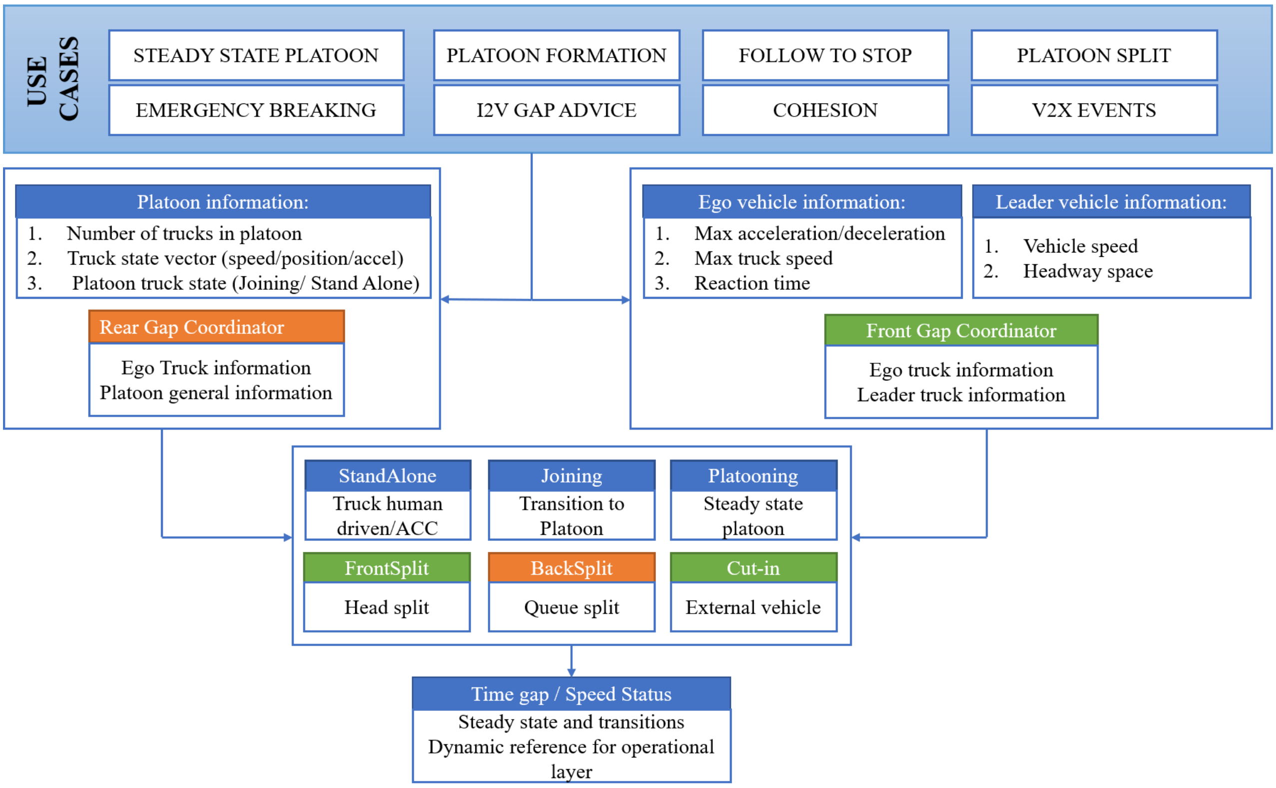


Figure 4. Tactical layer framework

3.2.4. Operational layer

Decisions taken by the state machine defined in the tactical layer are transformed into time gap and speed values that are recovered as an entry point for the operational layer, which interconnects high-level decisions from the general platoon with low level control decisions operated by the Adaptive Cruise Control (ACC) and its cooperative counterpart (CACC) when platoons are created. Heterogeneity is considered by modelling specific aspects of the truck dynamics such as acceleration bounds or vehicle speed distribution. These quantities depend on both truck static parameters such as weight, load, engine power and deceleration capabilities and truck state variables such as previous speed and gear.

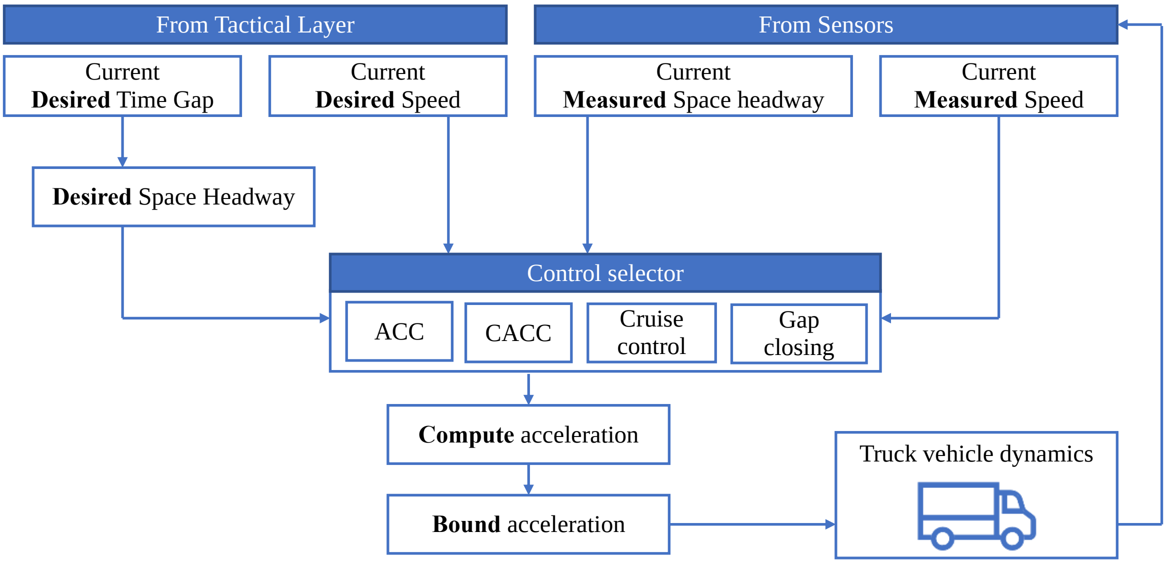


Figure 5. Operational layer framework

Figure 5 illustrates the specific workflow implemented in this case. Reference time gaps coming from the tactical layer (setting of the ACC, typically 1.5 s) are transformed into desired space headways, the desired speed is also transmitted to the local controller. Virtual sensors enabled in each truck measure speed and estimate the current headway space. By combining the desired values with the current ones, the local ACC computes the control acceleration that should be applied to the truck. A subspace of accelerations is considered by fixing boundaries depending on the vehicle brand or specific vehicle parameters. The loop is then closed by applying the acceleration and evolving the truck dynamics. This stage as explained later is pushed into the traffic simulator, so the evolution of non-platoon vehicles is also computed.

3.2.5. Authority transition

An authority transition block is designed to determine whether the vehicle will be controlled by automated systems or a human driver in the next time step, by evaluating the driving environment and vehicle/system performance. It allows a switch between automated driving and manual driving in a simulated automated vehicle, mimicking the real operation of automated vehicles in a mixed traffic environment especially at the low levels of driving automation. Based on the complex decision-making process, a multi-layer architecture is proposed (illustrated in Figure 4), integrating the various authority transition classifications, driving scenarios, driver decision/willingness and driver behavioural assumptions.

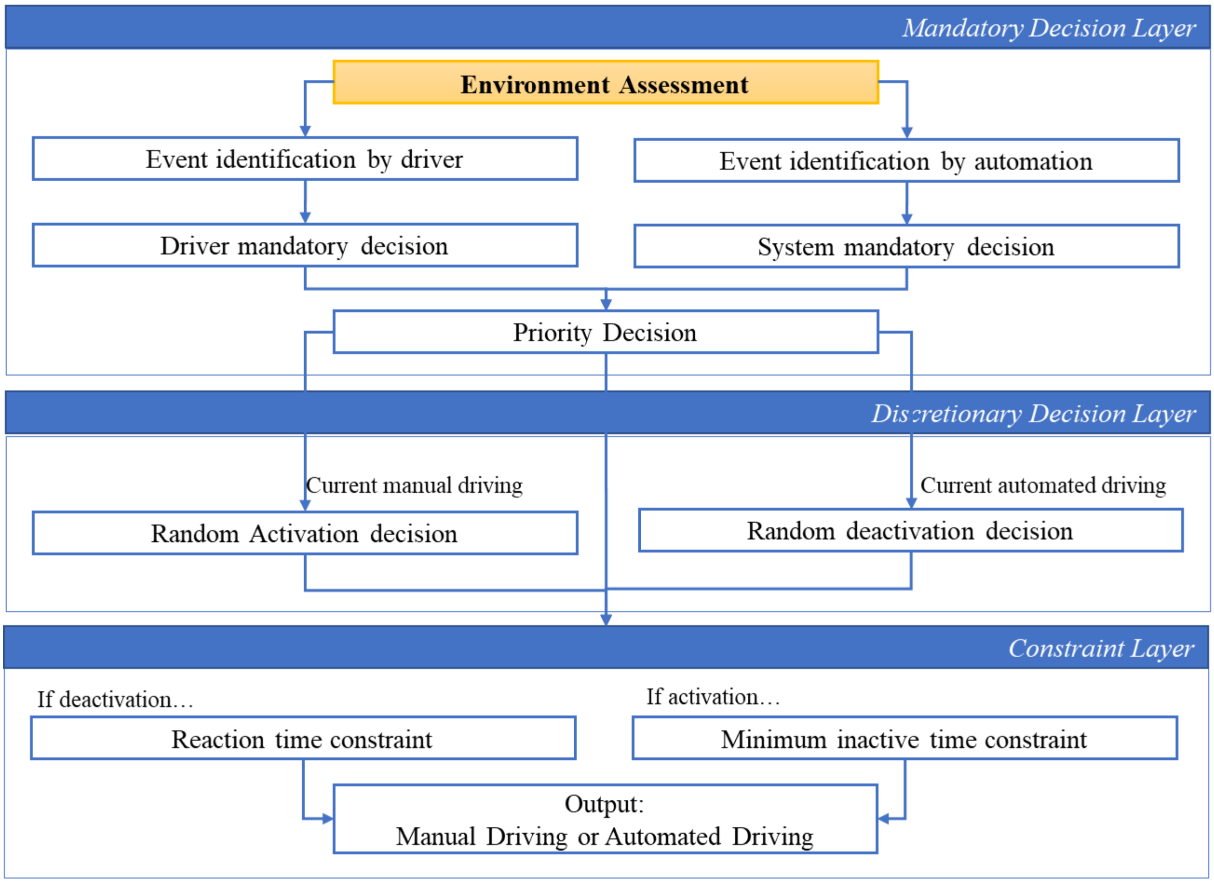


Figure 6. Authority transition framework

The Authority transition model is designed as a decision model, generating the decision of "manual control" or "automated control" at each time step. Mandatory decisions and discretionary (optional) decisions are structured as two different layers of the decision-making and a transition constraint layer is designed to model the delay between generating a decision and the realization:

- The authority transition model starts with the mandatory decision layer, where a decision has to be made as a response to certain events/driving situations. Two parallel paths are designed, being driver-initiated decision path and system-initiated decision path. Each path goes through an event identification block and a decision block and the decisions from two paths are prioritized in a final priority decision block.

- The second layer is a discretionary decision layer, where decisions are made by the driver's will instead of by the driving environment. At any moment, a driver is able to activate or deactivate the automated driving system, when no mandatory decision has to be made. The discretionary decision is modelled as a random event.

- A layer of transition constraints is designed as a bottom layer in the architecture, modelling the time delay from decision to realization. A reaction time is assumed when the vehicle control is passed from automated driving systems to human driving, and a minimum inactive time is assumed after the driver takes over.

3.2.6. Integration

Finally, the integration layer is presented in Figure 7, where the full blocks are presented in an interconnected way. First, the interface performs a request of data to the simulator by asking the current traffic state at time t. This step will generate vehicles, vehicle routing and traffic assignment according to the demand profile, providing the current vehicle state for all vehicles in the simulation. Once information is provided, an assessment environment determines the activation of platoons for ego trucks suitable and desiring to form a platoon. This aspect regulates the transition between the regular human driven model, or the platoon closed loop shown in Figure 5 and Figure 6. Information from the environment is transmitted to the tactical layer via the Front and Rear Gap coordinators as well as external perturbations such as cut-in vehicles. This information creates a use case that determines the decision process of the tactical layer. Low level control is performed updating states of platoon-controlled vehicles. This information is pushed back to the simulator so the traffic platform may compute the dynamic evolution of other vehicles currently present in the network. Once this process is completed, the full cycle starts again in a dynamic evolution evolving a single time step. The framework is able to handle specific events that can be sent to the vehicles such as an emergency stop or a manual condition for drivers to leave the platoon. In this case such events interrupt the platooning process by imposing the human driven behaviour.

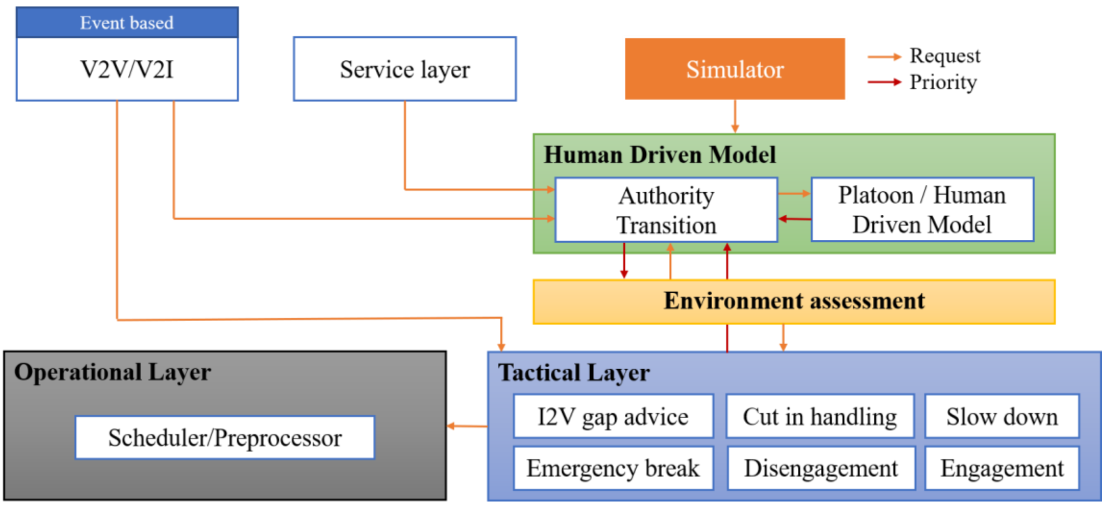


Figure 7. Integration of the full framework

3.3. Scenario description and results

As explained before, the simulation framework is used to determine the traffic flow effects of multi-brand truck platooning on a realistic highway corridor with an on-ramp which are the main locations of congestions and subsequent bottlenecks in a highway network. A number of scenarios has been proposed to evaluate these effects under different circumstances.

Several research assumptions are made to simplify the evaluation scenarios and narrow down the evaluation scopes.

- Multi-brand truck platoons are only allowed in the rightmost lane of mainline roads and trucks in a platoon do not intend to change lanes.
- ENSEMBLE trucks will be generated individually at the beginning of the network already being part of a platoon. A truck platoon is generated following a statistical distribution with randomness until the maximum platoon length is reached.
- ENSEMBLE trucks will not be generated on the on-ramp.

3.3.1. Merging scenario

The goal of the merging scenario evaluation is to evaluate the impacts of truck platoon manoeuvres at a typical merging bottleneck. This scenario focuses on the vehicle behaviour under stable platooning and cut-in conditions to investigate the potential advantages and disadvantages of applying multi-brand truck platoons at merging bottlenecks.

Generally, vehicles merging with the mainline traffic at on-ramps cause periodic congestions on highway corridors resulting in bottlenecks and thus impacting traffic flow efficiency. Hence, a typical simplified highway merging bottleneck is chosen as the simulation network as in Figure 8. A three-lane mainline road of 6.25 km long is considered (the first 1.5 km is the warm-up section) with a one-lane on-ramp connected to the mainline at 4 km. An acceleration lane of 250 m is assumed as an extended lane for the merging section to facilitate the lane changes from on-ramps. The lane change from the mainline to the acceleration lane is not allowed. The speed limit for passenger cars is 120 km/h and for trucks is 80 km/h. Detectors are placed at each lane every 500 m after the warm-up section. All detectors provide average 5-minute data for flow and speed. Simulated vehicle trajectories, such as position, speed and acceleration, will be collected from 1.5 km to the end of the network at every 0.1 seconds.

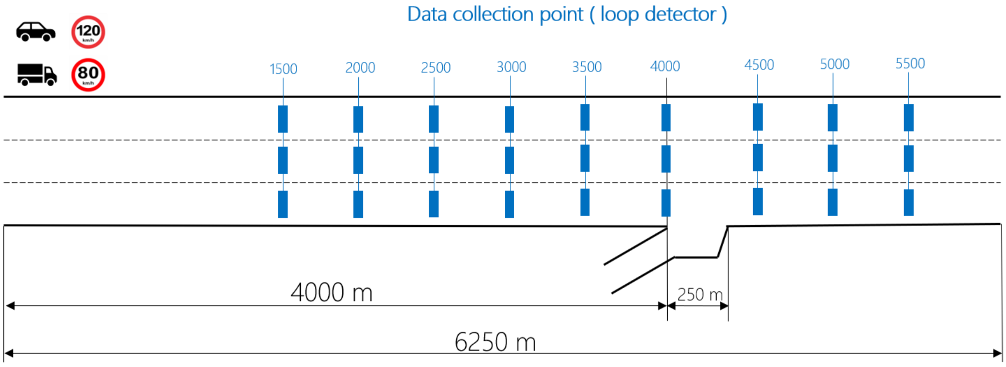


Figure 8. Merging bottleneck simulation network configuration

To explore the traffic impacts of truck platoon operation at a merging bottleneck, a simulation experiment taking the platoon level as the main control variable is designed. The platoon level is distinguished by a following time gap of 1.0 second for the Platooning Autonomous Function (PAF) and by a following time gap of 1.5 seconds for the Platooning Support Function (PSF). The two platooning functions and their specifications are described in detail in deliverables D2.3 (Willemsen, 2022) and D2.5 (Mascalchi E., 2022). Other than platoon level, the truck ratio is also taken as a control variable, increasing from 10% to 30% to represent a realistic mixed traffic flow and an extreme mixed traffic flow. The hypothesis behind the design is that the impact of a truck platoon might not be significant in the 10% truck ratio scenario, since the ENSEMBLE trucks do not reach a certain amount in the mixed traffic to achieve an aggregated influence. The market penetration rate of ENSEMBLE trucks is assumed as 20%, an expectation of truck platooning application in the future. The maximum platoon length is assumed as 7. Table 1 provides an overview of simulation runs with different platoon levels, platoon lengths and truck ratios.

Table 1 Overview of simulation runs with experiment variables

Simulation runs	**Truck Ratio 10%**	**Truck Ratio 30%**
Reference case	TR10Ref	TR30Ref
Platooning Support Function (PSF) *(1.5 second time gap)*	TR10TG15	TR30TG15
Platooning Autonomous Function (PAF) *(1.0 second time gap)*	TR10TG10	TR30TG10

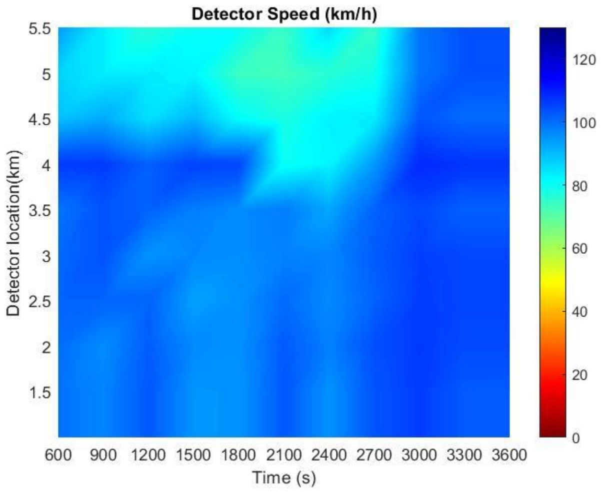
Two reference simulation cases are conducted respectively, at 10% and 30% truck ratios. To evaluate the impact on both capacity and traffic congestion, we tune the mainline demand and the on-ramp demand in the case of 30% truck ratio to invoke a full development of traffic congestion, from formation to dissolution. The mainline demand starts at 5100 veh/h (3 lanes) for 15 mins, increases to 5400 veh/h and lasts for 30 min, then reduces to 4500 veh/h within the last 15 min. The on-ramp demands are 800, 900 and 400 veh/h accordingly. The truck ratio of the on-ramp traffic is fixed at 5%. The same demand settings are used in the reference case with a 10% truck ratio, where no severe congestion is expected.

In total, six traffic scenarios are simulated with three repetitions for each scenario with different random seeds. The random seed decides the arriving time of vehicles at the network, as well as the vehicle desired speed, creating randomness in traffic dynamics. The simulation is conducted with a time step of 0.1 seconds and lasts for 1 hour. The first 5 min in the simulation is the warm-up period that vehicles need to fill up the network, where trajectory and detector data will be excluded.

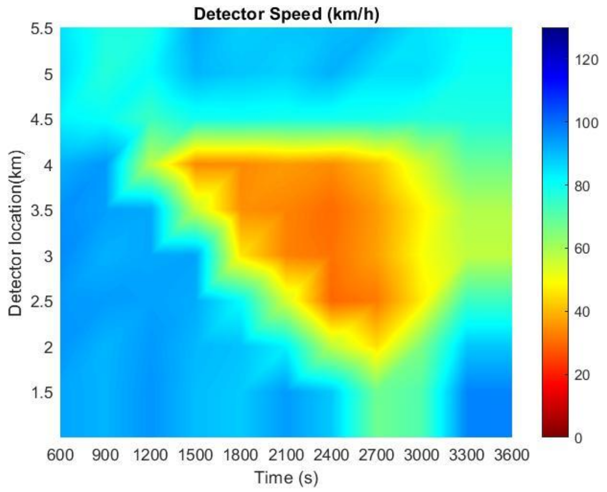
3.3.2. Simulation Results

To answer the research question of “What are the impacts of platooning levels on traffic flow performance?”, the comparisons of simulation results with 1.5 s and 1.0 s following gaps are firstly discussed. The congestion patterns are firstly illustrated for the overall traffic flow performance at the simulated merging bottleneck, shown in Figure 9.

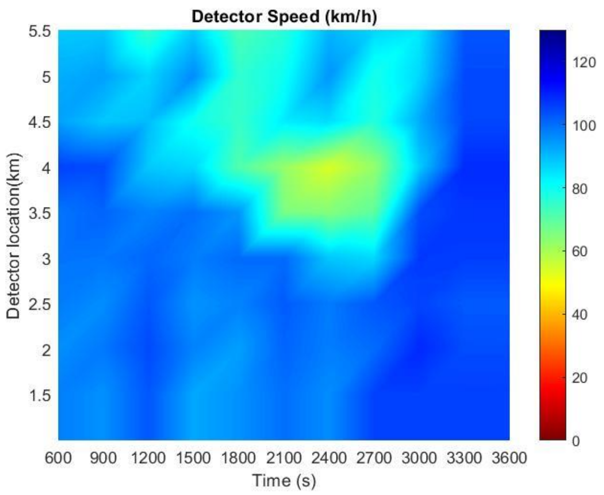
Traffic flow performance, especially the traffic congestion patterns, are substantially influenced by the operation of multi-brand truck platoons. As observed in Figure 9, replacing 20% of the normal trucks with ENSEMBLE truck platoons, results in different congestion formation time and location, congestion severities and the area where congestion propagates to. In the case of a 10% truck ratio, multi-brand truck platoons show little positive influence on traffic flow performance. Traffic flow speeds are reduced at the merging bottleneck when the truck platoons are introduced. This could be explained by the reduced merging efficiency due to that (1) trucks in a platoon will not provide cooperative maneuvers to facilitate merging vehicles and (2) merging vehicles have to reduce their speeds to wait until a platoon of 7 trucks passes, such that their speeds when entering the mainline traffic are much lower than the free-flow speeds.



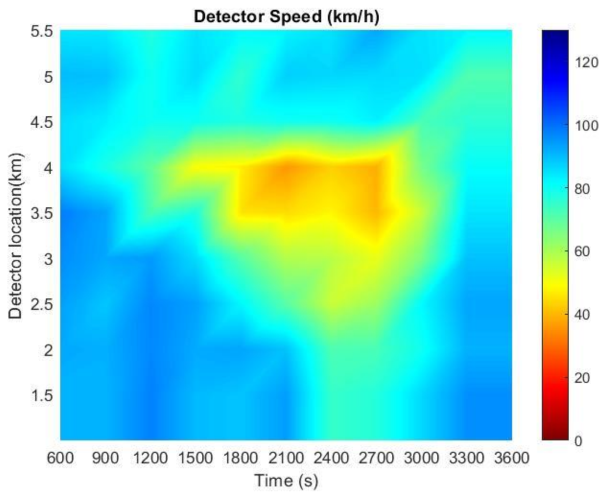
(a) Reference case: truck rate 10%



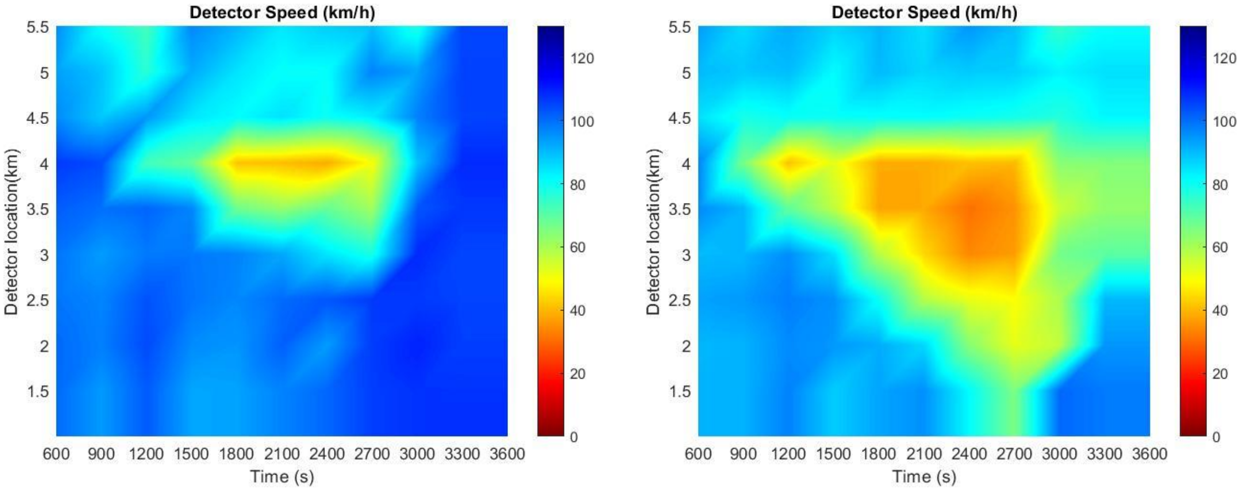
(b) Reference case: truck rate 30%



(c) TR10TG15



(d) TR30TG15



(e) TR10TG10 (f) TR30TG10

Figure 9. Traffic congestion patterns (harmonic speed in spatiotemporal plot) in simulations

The impacts of truck platoons on reducing traffic congestions are positive and substantial when the truck ratio in mixed traffic is large. Comparing the (b), (d) and (f) in Figure 9, the traffic congestions last less and the areas where congestion propagated to are smaller, when 20% of trucks are replaced by platoons with a length of 7. Especially in Figure 9 (d), the traffic congestion appears 5 minutes later than in the reference case and the traffic congestion is considerably less severe. It suggests that the road capacity increases, and that traffic breakdown can be postponed. The throughput after congestion happened, also increases, and traffic flow speed reduction decreases, all due to the existence of multi-brand truck platoons. This provides the first evidence of multi-brand truck platoons in improving road capacity and traffic congestion.

The impact of truck platoons on mitigating traffic congestion are different when truck platoons are operated at different platoon levels. As observed from Figure 9 (d) and (f), truck platoons at a higher level with smaller following gaps show less influence on traffic congestion patterns than platoons at a lower level with larger following gaps. A possible explanation is that the vehicles coming from the on-ramps are less likely to find suitable gaps to merge due to the short gaps between platoon trucks. A platoon of 7 trucks with short following gaps acts as one moving object when passing a merging section, such that vehicles intend to merge will have to slow down and wait for a gap until the platoon has passed. This can result in a low cut-in speed of a merging vehicle when it eventually enters the mainline traffic. Lower cut-in speed of a merging vehicle puts larger disturbances on the mainline traffic. Traffic congestion therefore can be easily triggered and propagate to a large area and last for a long period. Such influences of platoon levels (following gaps) pertain to both 10% and 30% truck ratio traffic.

Table 2 Road capacity and queue discharge rate at different platoon levels

	TR10Ref	TR10TG15	TR10TG10	**TR30Ref**	TR30TG15	TR30TG10
Capacity (veh/h)	**6331**	6233	6227	**6002**	6176	6128

Queue Discharge Rate (veh/h)	**6205**	5998	6069	**5722**	5776	5793
Capacity Drop	**0,84%**	3,72%	2,5%	**4,67%**	6,45%	5,47%

The quantitative effects of truck platoons on traffic flow efficiency can be taken from Table 2, where the capacity, queue discharge rate and capacity drop are listed. At a 10% truck ratio, road capacity and queue discharge rate decrease at both platoon levels when truck platoons are introduced. The reductions of capacity and queue discharge rate are around 1.6% and 2.9% respectively, and the capacity drop increases significantly from 0.84% to near 3%. The differences of capacity, queue discharge rate and capacity drop between the two following gaps of 1.5 seconds and 1 second are insignificant, implying a comparable traffic efficiency reduction at two platoon levels. A possible explanation is that the differences are easily mitigated by the randomness in traffic dynamics at a small number (2%) of ENSEMBLE trucks in the overall traffic. At a 30% truck ratio, the road capacity increases significantly with an average increase of 2.5%, while the variations of queue discharge rate are small. It naturally leads to an increased difference between the capacity and queue discharge rate, a large capacity drop. It suggests that a multi-brand truck platoon can be effective in preventing or postponing traffic congestion but have less influence after traffic congestion takes place. Overall, multi-brand truck platoons can improve the traffic flow operation when trucks take up a considerable percentage of the traffic, however, it can deteriorate traffic flow performance at a realistic truck ratio of 10%. This conclusion is in alignment with the observed traffic congestion patterns in Figure 9.

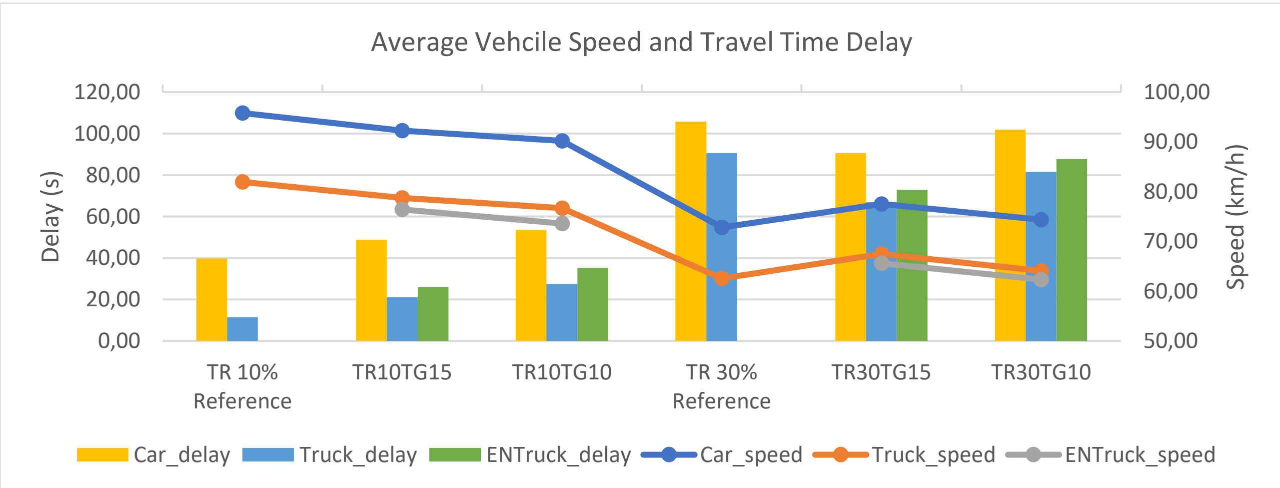


Figure 10. Average speed and travel time delay in simulations

Mobility benefits of platooning trucks can be revealed by the key performance indicators of vehicle speed and travel time delay. In Figure 10, the average speed and delay for each vehicle type are illustrated by the dot lines and bars separately. Overall, the average speeds and travel time delay vary with traffic congestion. The more severe congestion types observed in Figure 9, the smaller average speed and larger delay for all vehicle types. There are considerable gaps between the speeds of cars and trucks since they follow different distributions of desired speed. A car intends to travel at around 100 km/h while a truck desires (and has to) to travel around 80 km/h. It is observed that the average speeds of ENSEMBLE trucks are lower than the speed of normal trucks in all cases, suggesting platooning operations do not bring extra mobility benefits. The lower speed of platooning trucks is due to the simulation assumptions that truck platoons are only allowed in the rightmost lane, while the normal trucks could use the second rightmost lane to overtake slow vehicles. The speed differences are relatively small in congested flow compared to those in free flow. The results imply that platooning operation could be less attractive for efficiency, especially in free flow, if platoons are only allowed in the rightmost lanes.

The travel time delay results provide quantitative proof that multi-brand truck platoons decrease the efficiency of mixed traffic with 10% trucks but increase the traffic efficiency when the truck ratio is relatively high (30%). With a platoon of 7 trucks following 1.5 second time gap, the travel time delay can be reduced up to 14% and 26% for cars and normal trucks, and the overall delay disregard vehicle types decreases from 102 s to 85 s (shown in **Error! Not a valid bookmark self-reference.**), a reduction of 16%. This considerable time saved by truck platoons is solid evidence of the potential mobility benefits.

Table 3 Travel time delay and vehicle stop per vehicle

	TR10Ref	TR10TG15	TR10TG10	**TR30Ref**	TR30TG15	TR30TG10
Delay (s/veh)	37,10	46,35	51,35	101,69	84,96	97,05
Stops (#/veh)	0,06	0,27	0,37	1,19	0,98	1,25

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Table 3 also lists the number of stops per vehicle in each simulation scenario. The vehicle stop significantly increases at a 10% truck ratio due to deteriorated flow operation, but decreases in the case with a 7-truck platoon at a 1.5 s time gap.

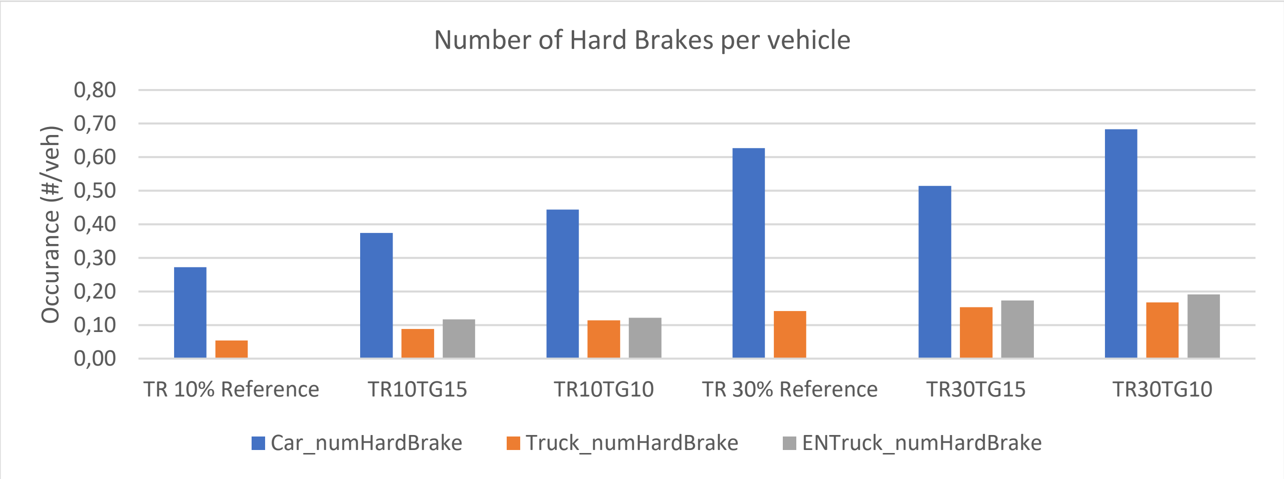

Figure 11. number of hard brakes per vehicle type in simulations

The number of hard brakes indicating traffic instability and traffic safety risk is presented in Figure 11 for each vehicle type. The occurrence of hard brakes generally increases with decreased traffic efficiency at both 10% and 30% truck ratios, due to the correlations between traffic efficiency and traffic flow stability. A large part of the increases is contributed by cars and minor increases are observed for trucks. It suggests that truck platoons, in terms of flow stability and safety, have a larger influence on cars than on trucks. The largest influence is observed in the case of 7-truck platoons at 1.5-second gap at the 30% truck ratio: the number of hard brakes per car reduces from 0.6 to 0.5, an increase of roughly 16%, related to a higher traffic safety.

Conclusions and suggestions for future work

This simulation experiment reveals the impacts of multi-brand truck platoons on traffic flow operation at a merging bottleneck. Main findings, insights and conclusions include:

- Traffic flow performance, especially the traffic congestion patterns, are substantially influenced by the operation of multi-brand truck platoons. The impacts of truck platoons on increasing road capacity, postponing and mitigating traffic congestions are substantial, especially when the truck ratios in mixed traffic is large (30%).

- Truck platoons can increase road capacity at a merging bottleneck at a 30% truck ratio, however, the increase of queue discharge rate is insignificant. It suggests that a multi-brand truck platoon can be more effective in preventing or postponing traffic congestion but have less influence after traffic congestion has occurred.

- When the truck ratio in traffic is around 10%, truck platoons can decrease road capacity and deteriorate traffic flow performance since a long truck platoon passing a merging area will reduce the probability of successful cut-ins at high speeds. The average speed of merging traffic is reduced when truck platoons are operated, and large disturbances are introduced when the merging vehicles eventually enter the mainline traffic.

- The impacts of truck platoons on mitigating traffic congestion are different for the two defined platooning functions. Truck platoons at autonomous function level (PAF) with smaller following gaps show fewer improvements on traffic congestion than platoons at a lower level (PSF) with larger following gaps. With small following gaps, the merging vehicles are less likely to find suitable gaps in between platooned trucks, and therefore they result in a lower cut-in speed that slows down mainline traffic.

- Truck platooning operations do not necessarily lead to higher (average) travelling speed than normal trucks. Platooned trucks experience slightly lower average speed when platoons are only allowed in the rightmost lanes.

- In terms of flow stability and safety (in terms of strong braking events), truck platoons have a larger influence on cars travelling at left-side lanes with high speeds than on trucks travelling at right-side lanes with low speeds. An increase of 16% in traffic safety is observed for cars in the case of platoons at a 1.5-second gap at the 30% truck ratio.

For future research, an interesting topic to be explored will be the impact of platoon length and vehicle market penetration rate on road capacity, traffic congestion and the traffic dynamics at the merging area. Meanwhile, effective lane management for truck platoons and advanced coordination between truck platoons and merging traffic could be investigated to facilitate truck platoon operations.

3.3.3. Conclusions

Truck platoons, as part of mixed traffic, are potentially able to increase road capacity and to postpone and mitigate traffic congestions. However, at merging areas we found that adverse impacts on road capacity can occur when merging traffic enters the mainline traffic with a lower speed. The impact largely depends on the penetration rate of trucks in the traffic flow and the platoon controller (lane management and platoon coordination).

Assuming 20% of the trucks are equipped trucks, impacts of platooning on traffic flow with a large truck ratio are more significant and positive, compared to the impacts with a small truck ratio. It suggests that the expected improvements and benefits from truck platoon operation are largely affected by the mixed traffic conditions. For truck platooning it is therefore more beneficial for traffic flow to be operated in the traffic where trucks take a large composition of the traffic, e.g., industry area or port area.

The impacts of truck platoons on road capacity were found to be different between support and autonomous platooning functions due to the difference in distance between the trucks. Truck platoons with a smaller following gap show fewer improvements to road capacity than platoons with a larger following gap at a merging bottleneck.

4. DATA COLLECTION PROCEDURES

4.1. General description

Traffic can be characterized at multiple scales: at microscopical scale specific vehicle interactions are aimed to be measured. At macroscopic level aggregated behaviors are intended to be examined. Example of microscopic characteristics are individual vehicle speed, space headway, acceleration. At a macroscopic level, aggregation of microscopic variables is regularly measured at fixed points in space.
In ENSEMBLE two kinds of real-life testing was planned: tests on test tracks and tests on public roads. Tests on tracks are focused on characterization of *dynamic performance and operation* of multi-brand truck platooning as well as the *platoon behavior during maneuvers.* The tests on public roads are intended to additionally measure the *impact on traffic flow & other road users*. In order to precisely capture traffic behavior, it is important to rely on both sources of information.

Mobile sensors aim to capture *microscopic information* via V2V communication and surrounding traffic conditions via *external sensors*. Fixed sensors are intended to capture historical/static traffic conditions and differentiate situations due to the presence of a truck platoon. This sensor scheme can be observed in **Error! Reference source not found.**.

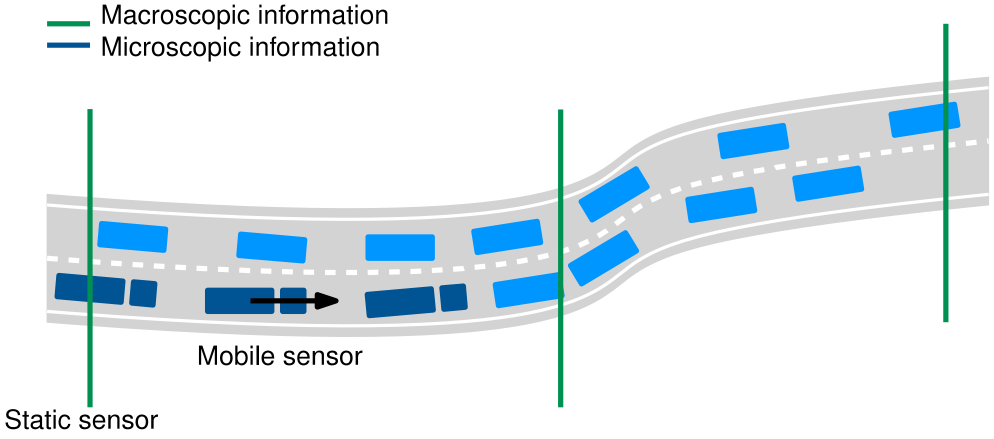

Figure 12. Platoon sensor scheme distribution

4.2. Objectives

The objective of the tests are:

- Measure the individual variability of headway space, speed and acceleration of a platoon of trucks in a platoon where the composition is characterized by different brands.
- Measure the total time taken to perform specific maneuvers in traffic.

- Examine and measure behaviors of traffic conditions surrounding a truck platoon. One example of such condition is: measuring the overtaking flow, or the relative differential speed between the trucks and the other vehicles on the road.
- Determine the achievable effect of truck platooning under real world conditions on the public road, in particular on traffic flow.

4.3. Suggested methods

In order to capture the surrounding traffic effects, two main methods have been proposed. The first one relies on laser technology to directly measure distance of surrounding vehicles. The second one is based on video where inter-vehicle distances are estimated in a post processing stage.

4.3.1. LIDAR based methods

In order to capture traffic phenomena measurements of traffic surrounding the platoon in the near vicinity should be performed. LIDAR technology is capable of measuring distance of the sensor with respect to interfering objects. The sensors can be installed either on the trucks or on supplementary vehicles to provide a cloud of sensor points. Given the situation where it is not possible to mount the sensors on the trucks, the scheme in Figure 13 is proposed. The figure describes two vehicles surrounding the platoon. Each one of the vehicles can be equipped with a lidar sensor to measure the traffic surrounding the full platoon formation. The main objective in this case is to determine the time taken to overtake the full platoon as well as count the number of vehicles passing the platoon in a stable formation.

The disadvantage of measurement in this scheme is to induce specific behaviors in drivers next to the platoon due to the additional conspicuous vehicles with the lidars, and hence modify the measured impact. A mitigating measure for that is to consider a distance to the platoon sufficiently big and within the range of the LIDAR sensor. It is important to highlight that in order to reduce the sensibility of the measurement to this scheme, the monitor vehicles should follow precisely the platoon speed.

Figure 13. Proposed measurement scheme for LIDAR sensors

This mechanism requires an advanced task of post processing via artificial intelligence / image processing due to the nature of the measurement. The cloud of points retrieved by both LIDAR sensors must be converted into information such as trajectories of detected vehicles, and in addition specific trajectories (varying traffic + first/last truck) must be extracted so that the inter-vehicle distance dynamics are well characterized. There is also a need to synchronize the clocks of both collecting vehicles to determine accurately the time taken to overtake as well as matching the trajectories of the vehicles in front and behind the formation.

4.3.2. Video-based methods

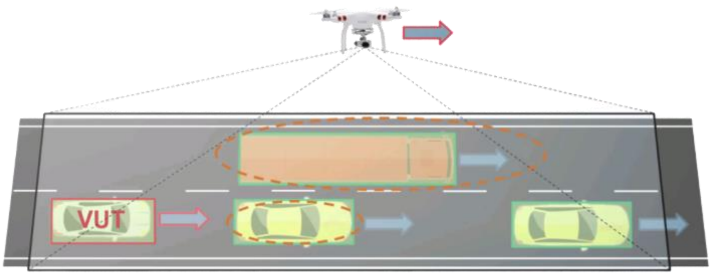

Figure 14. Proposed measurement scheme for Video based methods (Drone case)

The objective of this approach is to measure the traffic surrounding the platoon in a non-invasive setup. In this case the objective is to rely on measurements captured via video filmed from above the platoon. In a static condition, it is possible to extract features of the video, distinguish vehicles and estimate trajectories, speeds and accelerations. The particular case has been tested and measured at fixed points on highways. In order to detect interactions between the platoon and the traffic, requires that the platoon is filmed constantly. One idea for this case is illustrated in Figure 14: via a drone. Due to flight permissions the drone had to be replaced by a helicopter or a manned aerial vehicle that satisfies the following requirements:

- Follow the truck platoon at a desired speed by ensuring video stability,
- Collect video data in a frame such that the traffic surrounding the platoon is measured at least 100 m in upstream and downstream directions.

It is important to highlight that a control that is able to identify and follow a specific truck at a determined speed is required. The risk encountered here is due to variations in the platoon speed due to traffic conditions.

4.3.3. Hybrid scheme

The two measurement mechanisms previously presented might need to be mixed in order to improve the accuracy of the reconstruction of the traffic system and keep a constant track of the impact of the platoon.

4.4. Requirements

4.4.1. Baseline requirements

In order to determine the impact on traffic flow it is desired to perform a data collection process that facilitates the calibration of traffic simulator tools. Traffic data collection prior to the experiment is important to understand the multiple traffic effects such as seasonal conditions, effects of incidents, congestion effects. Recurrent traffic conditions provide a useful way to understand how the road infrastructure is used and its level of performance. In terms of traffic the variables related to macroscopic behavior of the traffic are suggested (see Table 5), variables of this type are non-local variables that aim to capture the full traffic condition at a given time.

Additionally, the baseline behavior of the platoon needs to be characterized. Typical calibration variables involve the dynamic behavior of the multi-brand platoon and its dynamic response to speed changes (see Table 4).

When executing the open road tests, it is important to collect data regarding the traffic surrounding the platoon, in particular inter-vehicle distance, or the time to overtake. The following section intend to summarize the reported information for better understanding or clarification.

4.4.2. Platoon Measurements

In order to capture the platoon behavior, measurements from the platoon vehicles are required. To this end, it is suggested to collect the following variables.

Variables / Signal	Source	Units	Sampling rate
Brake activation	Vehicle OBD	Binary	-
Throttle position	Vehicle OBD	0-100%	100 ms
Gear	Vehicle OBD	Integer number	100 ms
Vehicle weight	Scale	Kg	1 time
Gap distance	Vehicle-Vehicle (V2V)	m	100 ms
Position in platoon	Vehicle-Vehicle (V2V)	Integer number	Event / change
Speed	Vehicle-Vehicle (V2V)	m/s	100 ms
Longitudinal acceleration	Vehicle-Vehicle (V2V)	m/s^2	100 ms

Coordinates GPS	Vehicle-Vehicle (V2V)	Degrees	100 ms
Lateral position	Vehicle-Vehicle (V2V)	Integer number / m	100 ms
Relative speed to leader	Vehicle-Vehicle (V2V)	m/s^2	100ms

Table 4 Required variables for platoon measurements

Sampling rates are proposed according to optimal values that ensure an optimal rate for model characterization, although tolerance may be admitted to some of them.

The measurements are intended to be collected for all trucks participating in platoon formation.

4.4.3. Traffic Measurements

Traffic measurements can be of two types. Local variables refer to traffic variables surrounding the platoon. In this case, measurements are taken in a coordinate framework referring to the speed of the platoon. Non-local variables refer to measurements taken in a static coordinate framework. These measurements aim to provide information and variable fluctuation at specific locations where the platoon is passing by.

Variables / Signal	Source	Units	Sampling rate	Variable type
Relative lateral Position of surrounding vehicles	LIDAR/Video	m	100 ms	Local
Relative longitudinal position of surrounding vehicles	LIDAR/Video	m	100 ms	Local
Time to overtake	LIDAR/Video	s	-	Local
Speed when overtaking	LIDAR/Video	m/s	100 ms	Local
Vehicle Flow	Loop data	m	1min ~ 6min	Non-local
Vehicle length distribution	Loop data	m	1min ~ 6min	Non-local
Occupancy	Loop data	%	1min ~ 6min	Non-local

Table 5 Required variables for traffic measurements

Traffic measurement data may involve processing of raw data of LIDAR/Video data or a fusion between two types of measurement, as explained before. Loop data is regularly used to establish a baseline

4.5. Requirements for calibration

In order to calibrate the traffic simulation tool, it is relevant to establish a baseline of traffic data. Basic requirements for this are:

- Network layout,
- Demand data,
- Special control,
- Seasonal data.

4.5.1. Network description

The network layout needs to be known with precision. In this case it is desired to provide a map containing the road infrastructure with the following characteristics.

- Road segment identification,
- Origin/End coordinates,
- Altitude,
- Curvature,
- Total segment length,
- Upstream/downstream connections,
- Number of lanes,
- Traffic flow direction.

The segments lengths may vary according to the geography, for this reason it is relevant to provide a resolution in a scale of 1:2000. One proposed mechanism for retrieving this data is via the OSMnx package available in open source (Boeing 2017).

Network layout from open data services such as Open Street Maps may require adaptation to the specified traffic simulation tool, but we consider that this information provides enough information to build the first baseline. Other characteristics may require light signals whenever they are available, or special traffic signs that may modify the traffic behavior.

4.5.2. Demand data

Traffic infrastructure needs to be populated with vehicles following particular paths. For this it is important to know:

Inflow at onramps / entry points: It corresponds to the number of vehicles entering to a road in a certain window of time. For better granularity estimations regularly correspond to vehicle counting in intervals from 1 to 5 minutes. In a more aggregated way vehicles can be counted per hour. The first case is mostly desired for better accuracy on traffic conditions.

Outflow at off ramps / exit points: It corresponds to the number of vehicles exiting from the road or taking offramps. Granularity is desired as inflow data.

Traffic assignment: In complex networks it is important to understand how drivers behave. Multiple ways have been determined for this. Estimation of Origin/Destination can be done based on survey data, or GPS data. This information is only required in the case of complex networks such as cities.

4.5.3. Special control policies

It is important to know in advance some control policies that are regularly fixed on certain roads such as variable speed limits, lane reduction restrictions, high occupancy lanes. They allow us to better understand and calibrate the dynamic behavior of traffic. The following descriptions intend to provide more details on required information when special policies are applied.

Variable speed limits: They refer to all existing panels that regulate speed limits on roads. In case the speed limit is modified via panels information regarding the time or condition to change the speed limit is required.

Lane management restrictions: In cases of infrastructure with limited capacity authorities reserve lanes for specific vehicle types such as buses or forbid circulation for specific vehicle types such as trucks. Some specific lane policies also impose specific speeds over lanes according to the vehicle type. The control can be imposed according to a fixed time window or a specified traffic condition.

High occupancy lanes: High occupancy lanes tend to favor passenger transportation in infrastructures where the efficient passenger car units per vehicle are very low. For such cases, some specific lanes are enabled for high occupancy vehicles (2 or more passengers). The net effect produced in this case is regularly a moving bottleneck and reduced lane changes.

4.5.4. Seasonal traffic data

Traffic behavior regularly obeys a seasonality that varies according to days of the weeks or months of the year. Variations of this regularity can be introduced by specific events such as incidents, special dates, mass populated events, weather conditions. For those reasons historical data is also important.

In order to better calibrate a traffic model, it is important to be able to distinguish multiple profiles or regimes. Data profiles of traffic during the full day different days of the week. In particular at the time where open road tests are going to be developed.

In summary, to be able to calibrate the traffic simulator it is necessary to know:

- Time series of average flow at entrances/exits of the highways classified per days of the week,
- Variance of the average flow during this time.

4.5.5. Required repetitions / Minimum test distance

For open road tests, the following use cases and their repetitions in order to provide more precision on the desired tests are summarized as:

Test situation	Test case	Test type	Driving time (min)	Required distance (Km)
Stability of the time gap	Platoon at specific gap	Test track + Open road	20	26
Transition time between two time gaps	Change platoon gap	Test track	20	25
Stability of the time gap with respect to speed variations	Change speed of leader when platooning	Test track + Open road	20	25
Reaction time of the platoon to cut-in maneuvers	Cut-in	Test track + Open road	> 5	2
Time taken to engage a platoon	Join from behind	Test track	10	>5
Time taken to disengage an existing platoon	Disengage	Test track	10	>5

Table 6 Specifications for different test situations

4.6. Research questions

In order to conduct the study of traffic impacts from the open road tests, we follow a methodology where Key Performance Indicators are designed according to provide answers to specific research questions. The main research question in the project is to provide highlights about: *What are the traffic flow effects of multi-brand truck platooning?*

As extended question the former one can be translated into, *what is the impact of truck platooning regarding*:

- Travel time of users of the network,
- Delays (difference between the free flow travel time and current travel time,
- Network throughput (flow at specific cross sections),
- Capacity (Effective modification on maximum flow at specific stops in the road network),
- Traffic flow stability (Effects on flow stability).

These are some of the questions that can be formulated in terms of performance indicators. The objective of this section is to provide some highlights on scenarios and test situations that could be of interest, as well as locations according to the suggested locations in the Catalonia Living Lab for the experimental setting.

4.7. Potential routes

We have considered three possible sites for open road testing and these are:

- C32 – Vendrell - Barcelona
- AP7 –Vendrell (Next to IDIADA) - Barcelona
- AP2 –Lleida – La Bisbal del Penedes

The sites proposed here are related to available information. Adaptation to the same kind of situations in other road networks is possible.

A route is defined as a sequence of points from a starting point to an ending point. Figure 15 and Figure 16 show the routes in a map for easy viewing.

Figure 15 – Itinerary A→ C → D →A (as indicated in the map)

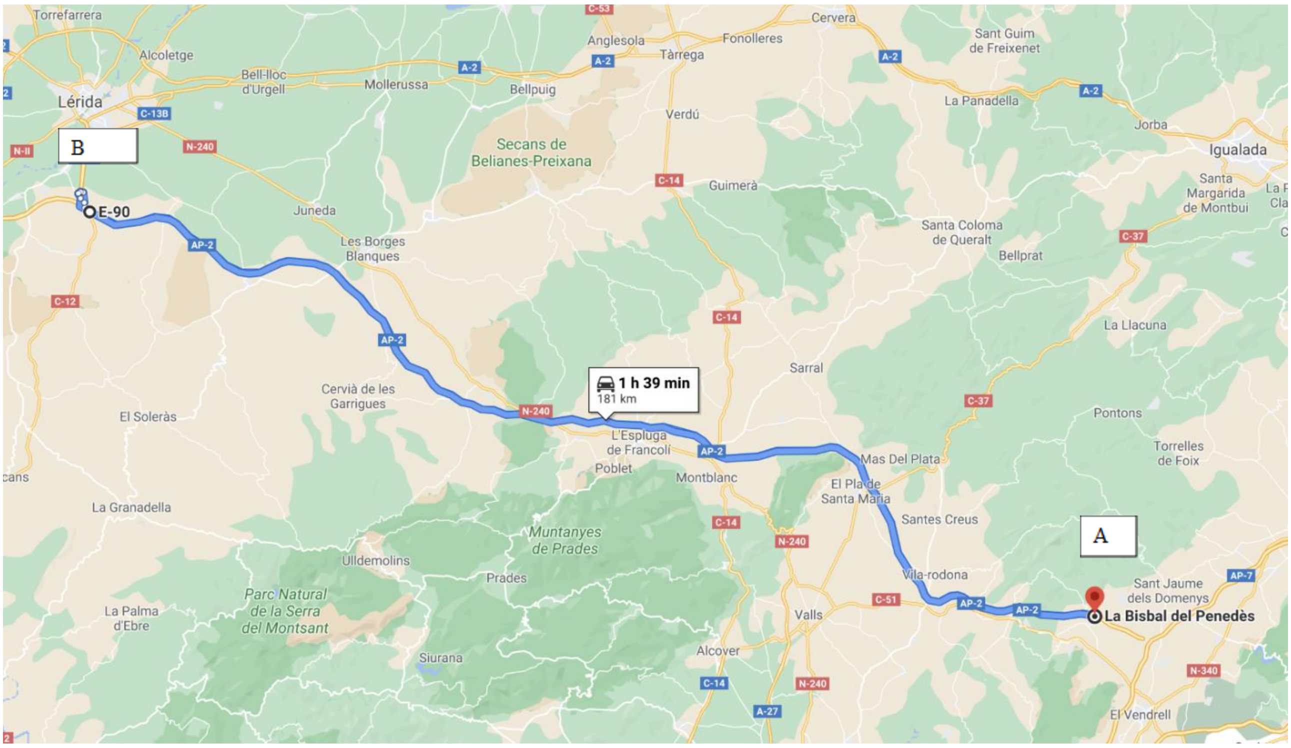

Figure 16 – Itinerary A→ B →A (as indicated in the map)

4.8. Video recording

This task will define the video shooting activity to be performed during the flight operation:

- **Recording Objective:** The objective of the recording is to observe the interactions of heavy trucks with the surrounding traffic during the duration of the experiment. The video will be recorded as much as possible from a vertical point of view so that the vehicles and the convoy of trucks can be observed from above (see Figure 8). If the flight conditions do not allow recording from this point of view, the objective will be to position the recording angle to place the convoy of trucks and the surrounding cars in the center of the image while avoiding occlusion of the vehicles (vehicles covered by other objects in the image).

- **Video quality:** The objective also will be to keep the aperture of the lens to have images with high sharpness and high quality. For the technical specifications on the video, the V14HD system will be the basic reference.

- **Recording check:** Each video will be checked at the end of each operation to note observations and information about the recording.

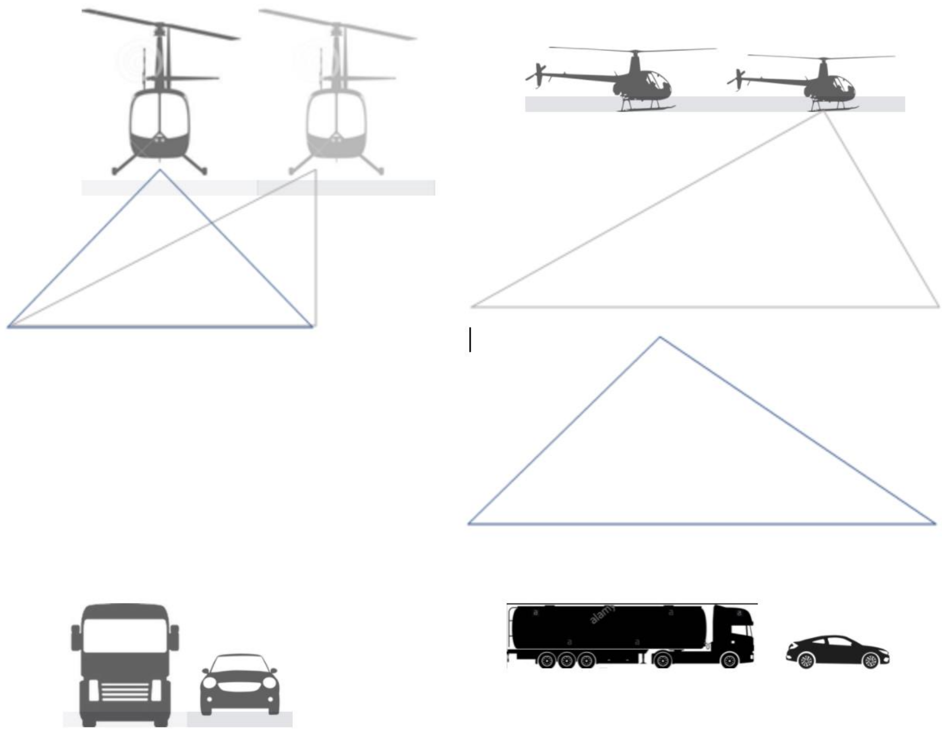

Figure 17 Viewpoint for recording the experimental operation

Figure 18 – Video sample of Open Road Tests

4.9. Observations from the LIDAR Data

A typical frame captured from the Lidar sensors while performing the open road tests is shown in Figure 19. The Lidar sensors equipped in the vehicles at the front and end of the truck platoon helped to analyse the overtaking flows and the behaviour of the vehicles while overtaking the truck platoon.

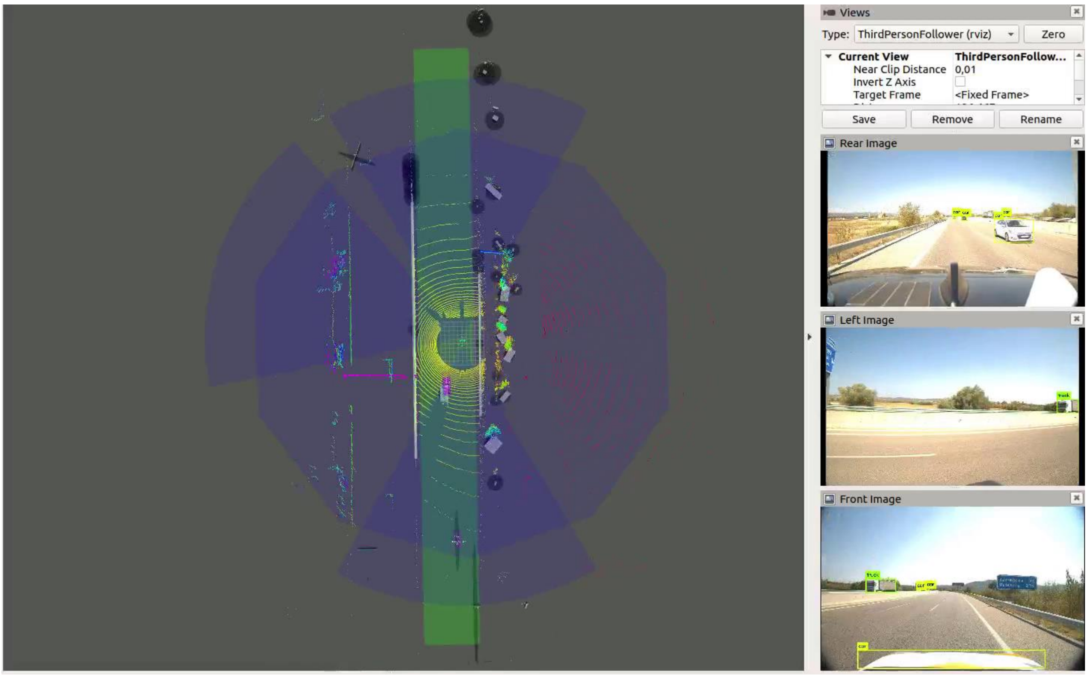

Figure 19 – A snapshot of the image recorded by the LIDAR sensor

The following table shows the percentage of vehicles overtaking the vehicle at the end of the platoon by vehicle type, for different test sections and on different times of the day during the field tests. These values have been recorded when the platoon speed was stable (i.e. around 70 km/h).

Vehicle Type	**Percentage Vehicles Overtaking**			
	20.09.2021 morning (AP2Lleida)	20.09.2021 midday (AP7_C32)	21.09.2021 morning (C32_AP7)	21.09.2021 midday (AP2Lleida)
Car	78%	75%	76%	82%
Truck	44%	60%	64%	56%

Table 7 Share of vehicles overtaking the truck platoon for different test locations

It may be observed that around 75% of all cars and 60% of all trucks have attempted to overtake the platoon at the current speed. However, as can be observed from the following figure, the percentage of vehicles overtaking is different depending on the lane they are in. When the vehicles are in the lanes to the left of the platoon, then the share of overtaking vehicles are higher. But it may be interesting to note that about 60% and 40% of cars and trucks, respectively, that are on the same or right lane of the truck platoon, also attempt to overtake. This indicates that, at the current speed of 70 km/h, the truck platoon acts like a moving bottleneck. This finding from the field test indicates that increasing the platoon speed to match the speed of the vehicles on the right lane may encourage fewer overtaking manoeuvres and improve the traffic flow impacts.

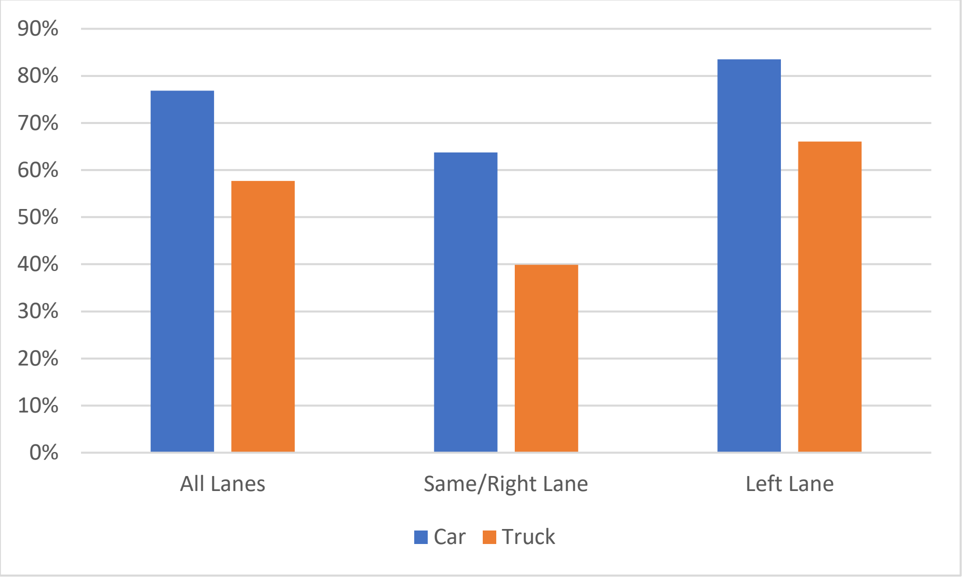

Figure 20 – Percentage of vehicles overtaking the rear vehicle of the truck platoon by vehicle type and lane

The LIDAR sensors may further be utilized to observe the type of manoeuvre adopted by the overtaking vehicle, especially in terms of lane selection and speed profile. The following figure, for example, shows a typical profile of a car (OV = overtaking vehicle) overtaking the test vehicle (TV). Initially the car follows the test vehicle, then it starts to increase speed while changing lanes, then at around 2.5 seconds, it is right next to the test vehicle at the peak speed, then once the overtaking action is complete the vehicle reduces the speed and leaves the overtaking lane and continues to drive at its desired speed that is about 15-20 km/h higher than the platoon speed.

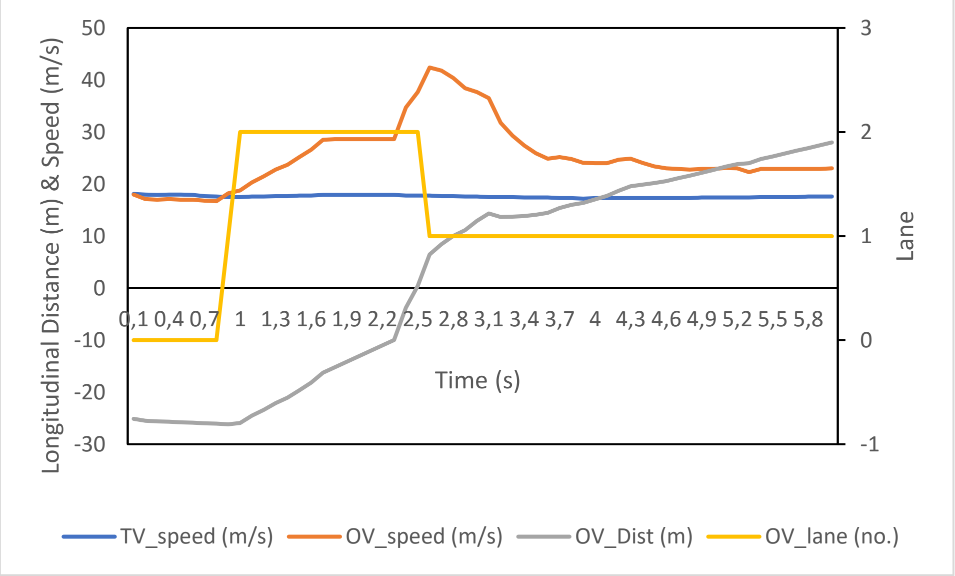

Figure 21 – Speed, longitudinal distance to test vehicle, and lane selection of overtaking vehicle

5. SUMMARY AND CONCLUSION

The main objective of this deliverable was to provide a general perspective on how multi-brand platoons can be integrated with traffic flow and quantify their impact in terms of traffic. This, in the future, can be used as a basis for creating real-time monitoring of truck platoons driving on roads under the mandate of road authorities in particular areas. The main idea has been focused on assessing mechanical effects of multi-brand platoons on traffic flow, such as infrastructure capacity and other traffic indicator effects based on several factors inherent to the platoon such as the composition, length, manoeuvre execution by means of a traffic simulator. This document describes the methodology implemented for conducting the assessment, and describes details on the implementation of the "white-label" truck implementation (specified by WP2 and detailed in deliverables D2.3 and D2.5) in the traffic simulator integrated in this evaluation. This so-called white-label truck incorporates the minimal requirements, framework, and interfaces for multi-brand platooning, in that it can serve as a model for forming, maintaining and dissolution of platoons, considering traffic and infrastructure requirements and road sections where platooning is allowed.

In order to assess the performances of multi-brand platooning strategies, the implementation of realistic traffic scenarios is conducted. Key performance indicators (KPI) are defined for measuring the impact specifically around discontinuities, e.g., merging areas, where congestion may be triggered. The list of KPIs include capacity, queue discharge rate, congestion pattern, from the road operator perspectives, and, vehicle speed, travel time delays, number of stops and hard brakings from the road user perspective.

A data collection plan is also presented in this document providing recommendations to perform Open Road Testing of the multi-brand platoon. Data collected in these experiments is used to provide qualitative evaluation of impact of the platoon.

ENSEMBLE micro simulation studies have shown that truck platoons, as part of mixed traffic, are potentially able to increase road capacity and to postpone and mitigate traffic congestions. The effect depends on the ratio of truck platoons as part of the total traffic and the location in the network. However, at merging areas, it has been observed that adverse impacts on road capacity can occur when merging traffic enters the mainline traffic with a lower speed. The impact largely depends on the penetration rate of trucks in the traffic flow and the platoon controller (lane management and platoon coordination).

Assuming 20% of the trucks are equipped trucks, impacts of platooning on traffic flow with a large truck ratio are more significant and positive, compared to the impacts with a small truck ratio. It suggests that the expected improvements and benefits from truck platoon operation are largely affected by the mixed traffic conditions. For truck platooning it is therefore more beneficial for traffic flow to be operated in the traffic where trucks take a large composition of the traffic, e.g., industrial areas or port areas.

The impacts of truck platoons on road capacity were found to be different between support and autonomous platooning due to the difference in distance between the trucks. Truck platoons with a smaller following gap show fewer improvements to road capacity than platoons with a larger following gap at a merging bottleneck.

The suggestion that follows from these conclusions is that it is beneficial for road capacity and traffic flow to avoid truck platooning on road segments with a lot of highway entries. Hub to hub platooning and platooning at night can be a very good solution.

Also, road operators can take advantage of platooning trucks to increase their road capacity by applying temporal larger following gaps near merging bottlenecks. The V2I communication possibility of platoons can be used to announce the presence of a platoon to the ramp-metering installations, such that these installations can adjust the traffic that is merging into the highway.

6. BIBLIOGRAPHY

Alam, A., B. Besselink, V. Turri, J. Martensson, and JK. H. Johansson. 2015. "Heavy-Duty Vehicle Platooning for Sustainable Freight Transportation." *IEEE Control Systems Magazine* 35 (6): 34–56. https://people.kth.se/~kallej/papers/vehicle_ieeecsm15.pdf.

Calvert, S. C., W. J. Schakel, and B. van Arem. 2019. "Evaluation and Modelling of the Traffic Flow Effects of Truck Platooning." *Transportation Research Part C: Emerging Technologies* 105 (March): 1–22. https://doi.org/10.1016/j.trc.2019.05.019.

Calvert, S. C., W. J. Schakel, and J. W.C. van Lint. 2017. "Will Automated Vehicles Negatively Impact Traffic Flow?" *Journal of Advanced Transportation* 2017. https://doi.org/10.1155/2017/3082781.

Čičić, Mladen, and Karl Henrik Johansson. 2019a. "Energy-Optimal Platoon Catch-up in Moving Bottleneck Framework." *2019 18th European Control Conference, ECC 2019* 1: 3674–79. https://doi.org/10.23919/ECC.2019.8795754.

Čičić, Mladen, and Karl Henrik Johansson. 2019b. "Stop-and-Go Wave Dissipation Using Accumulated Controlled Moving Bottlenecks in Multi-Class CTM Framework." *Proceedings of the IEEE Conference on Decision and Control* 2019-Decem: 3146–51. https://doi.org/10.1109/CDC40024.2019.9029216.

Duret, Aurelien, Meng Wang, and Andres Ladino. 2018. "A Hierarchical Approach for Splitting Truck Platoons near Network Discontinuities." *Transportation Research Procedia* 38 (July): 627–46. https://doi.org/10.1016/j.trpro.2019.05.033.

Duret, Aurelien, Meng Wang, and Andres Ladino. 2020. "A Hierarchical Approach for Splitting Truck Platoons near Network Discontinuities." *Transportation Research Part B: Methodological* 132: 285–302. https://doi.org/10.1016/j.trb.2019.04.006.

European Comission. 2016. "A European Strategy for Low-Emission Mobility." *European Comission*. Brussels, Belgium.

Jin, Li, Mladen Čičić, Karl H. Johansson, and Saurabh Amin. 2020. "Analysis and Design of Vehicle Platooning Operations on Mixed-Traffic Highways." *ArXiv*. https://doi.org/10.1109/tac.2020.3034871.

Joselow, Maxine. 2021. "Five Big Takeaways from COP26 - The Washington Post." *The Washington Post*. https://www.washingtonpost.com/politics/2021/11/15/five-big-takeaways-cop26/.

Kunze, Ralph, Richard Ramakers, Klaus Henning, and Sabina Jeschke. 2009. "Organization and

Operation of Electronically Coupled Truck Platoons on German Motorways.” *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* 5928 LNAI (June): 135–46. https://doi.org/10.1007/978-3-642-10817-4_13.

Mascalchi E., et. al. (2022). *Final Version Functional specification for white-label truck), D2.5 of H2020 project ENSEMBLE.*

Milanés, Vicente, and Steven E. Shladover. 2014. “Modeling Cooperative and Autonomous Adaptive Cruise Control Dynamic Responses Using Experimental Data.” *Transportation Research Part C: Emerging Technologies* 48: 285–300. https://doi.org/10.1016/j.trc.2014.09.001.

Ramezani, Hani, Steven E. Shladover, Xiao Yun Lu, and Osman D. Altan. 2018. “Micro-Simulation of Truck Platooning with Cooperative Adaptive Cruise Control: Model Development and a Case Study.” *Transportation Research Record* 2672 (19): 55–65. https://doi.org/10.1177/0361198118793257.

Treiber, Martin, and Arne Kesting. 2013. *Traffic Flow Dynamics*. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-32460-4.

Tsugawa, Sadayuki, Sabina Jeschke, and Steven E. Shladover. 2016. “A Review of Truck Platooning Projects for Energy Savings.” *IEEE Transactions on Intelligent Vehicles* 1 (1): 68–77. https://doi.org/10.1109/TIV.2016.2577499.

Wang, Meng, Honghai Li, Jian Gao, Zichao Huang, Bin Li, and Bart Van Arem. 2018. “String Stability of Heterogeneous Platoons with Non-Connected Automated Vehicles.” *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC* 2018-March: 1–8. https://doi.org/10.1109/ITSC.2017.8317792.

Willemsen, D. Schmeitz, A. et al., (2022). *V2 Platooning use cases, scenario definition and Platooning Levels. D2.3 of H2020 project ENSEMBLE.*

7. APPENDIX A

7.1. Glossary

7.1.1. Definitions

Term	Definition
Convoy	A truck platoon may be defined as trucks that travel together in convoy formation at a fixed gap distance typically less than 1 second apart up to 0.3 seconds. The vehicles closely follow each other using wireless vehicle-to-vehicle (V2V) communication and advanced driver assistance systems
Cut-in	A lane change manoeuvre performed by vehicles from the adjacent lane to the ego vehicle's lane, at a distance close enough (i.e., shorter than desired inter vehicle distance) relative to the ego vehicle.
Cut-out	A lane change manoeuvre performed by vehicles from the ego lane to the adjacent lane.
Cut-through	A lane change manoeuvre performed by vehicles from the adjacent lane (e.g. left lane) to ego vehicle's lane, followed by a lane change manoeuvre to the other adjacent lane (e.g. right lane).
Ego Vehicle	The vehicle from which the perspective is considered.
Emergency brake	Brake action with an acceleration of <-4 m/s2
Event	An event marks the time instant at which a transition of a state occurs, such that before and after an event, the system is in a different mode.
Following truck	Each truck that is following behind a member of the platoon, being every truck except the leading and the trailing truck, when the system is in platoon mode.
Leading truck	The first truck of a truck platoon
Legal Safe Gap	Minimum allowed elapsed time/distance to be maintained by a standalone truck while driving according to Member States regulation (it could be 2 seconds, 50 meters or not present)
Manoeuvre ("activity")	A particular (dynamic) behaviour which a system can perform (from a driver or other road user perspective) and that is different from standing still, is being considered a manoeuvre.

Term	Definition
ODD (operational design domain)	The ODD should describe the specific conditions under which a given automation function is intended to function. The ODD is the definition of where (such as what roadway types and speeds) and when (under what conditions, such as day/night, weather limits, etc.) an automation function is designed to operate.
Operational layer	The operational layer involves the vehicle actuator control (e.g. accelerating/braking, steering), the execution of the aforementioned manoeuvres, and the control of the individual vehicles in the platoon to automatically perform the platooning task. Here, the main control task is to regulate the inter-vehicle distance or velocity and, depending on the Platooning Level, the lateral position relative to the lane or to the preceding vehicle. Key performance requirements for this layer are vehicle following behaviour and (longitudinal and lateral) string stability of the platoon, where the latter is a necessary requirement to achieve a stable traffic flow and to achieve scalability with respect to platoon length, and the short-range wireless inter-vehicle communication is the key enabling technology.
Platoon	A group of two or more automated cooperative vehicles in line, maintaining a close distance, typically such a distance to reduce fuel consumption by air drag, to increase traffic safety by use of additional ADAS-technology, and to improve traffic throughput because vehicles are driving closer together and take up less space on the road.
Platoon Automation Levels	In analogy with the SAE automation levels subsequent platoon automation levels will incorporate an increasing set of automation functionalities, up to and including full vehicle automation in a multi-brand platoon in real traffic for the highest Platooning Automation Level. The definition of "platooning levels of automation" will comprise elements like e.g. the minimum time gap between the vehicles, whether there is lateral automation available, driving speed range, operational areas like motorways, etc. Three different levels are anticipated; called A, B and C.
Platoon candidate	A truck who intends to engage the platoon either from the front or the back of the platoon.
Platoon cohesion	Platoon cohesion refers to how well the members of the platoon remain within steady state conditions in various scenario conditions (e.g. slopes, speed changes).
Platoon disengaging	The ego-vehicle decides to disengage from the platoon itself or is requested by another member of the platoon to do so. When conditions are met the ego-vehicle starts to increase the gap between the trucks to a safe non-platooning gap. The disengaging is completed when the gap

Term	Definition
	is large enough (e.g. time gap of 1.5 seconds, which is depends on the operational safety based on vehicle dynamics and human reaction times is given). A.k.a. leave platoon
Platoon dissolve	All trucks are disengaging the platoon at the same time. A.k.a. decoupling, a.k.a. disassemble.
Platoon engaging	Using wireless communication (V2V), the Platoon Candidate sends an engaging request. When conditions are met the system starts to decrease the time gap between the trucks to the platooning time gap. A.k.a. join platoon
Platoon formation	Platoon formation is the process before platoon engaging in which it is determined if and in what format (e.g. composition) trucks can/should become part of a new / existing platoon. Platoon formation can be done on the fly, scheduled or a mixture of both. Platoon candidates may receive instructions during platoon formation (e.g. to adapt their velocity, to park at a certain location) to allow the start of the engaging procedure of the platoon.
Platoon split	The platoon is split in 2 new platoons who themselves continue as standalone entities.
Requirements	Description of system properties. Details of how the requirements shall be implemented at system level
Scenario	A scenario is a quantitative description of the ego vehicle, its activities and/or goals, its static environment, and its dynamic environment. From the perspective of the ego vehicle, a scenario contains all relevant events. Scenario is a combination of a manoeuvre (“activity”), ODD and events
Service layer	The service layer represents the platform on which logistical operations and new initiatives can operate.
Specifications	A group of two or more vehicles driving together in the same direction, not necessarily at short inter-vehicle distances and not necessarily using advanced driver assistance systems
Steady state	In systems theory, a system or a process is in a steady state if the variables (called state variables) which define the behaviour of the system or the process are unchanging in time. In the context of platooning this means that the relative velocity and gap between trucks is unchanging within tolerances from the system parameters.

Term	Definition
Strategic layer	The strategic layer is responsible for the high-level decision-making regarding the scheduling of platoons based on vehicle compatibility and Platooning Level, optimization with respect to fuel consumption, travel times, destination, and impact on highway traffic flow and infrastructure, employing cooperative ITS cloud-based solutions. In addition, the routing of vehicles to allow for platoon forming is included in this layer. The strategic layer is implemented in a centralized fashion in so-called traffic control centres. Long-range wireless communication by existing cellular technology is used between a traffic control centre and vehicles/platoons and their drivers.
Tactical layer	The tactical layer coordinates the actual platoon forming (both from the tail of the platoon and through merging in the platoon) and platoon dissolution. In addition, this layer ensures platoon cohesion on hilly roads, and sets the desired platoon velocity, inter-vehicle distances (e.g. to prevent damaging bridges) and lateral offsets to mitigate road wear. This is implemented through the execution of an interaction protocol using the short-range wireless inter-vehicle communication (i.e. V2X). In fact, the interaction protocol is implemented by message sequences, initiating the manoeuvres that are necessary to form a platoon, to merge into it, or to dissolve it, also taking into account scheduling requirements due to vehicle compatibility.
Target Time Gap	Elapsed time to cover the inter vehicle distance by a truck indicated in seconds, agreed by all the Platoon members; it represents the minimum distance in seconds allowed inside the Platoon.
Time gap	Elapsed time to cover the inter vehicle distance by a truck indicated in seconds.
Trailing truck	The last truck of a truck platoon
Truck Platoon	Description of system properties. Details of how the requirements shall be implemented at system level
Use case	Use-cases describe how a system shall respond under various conditions to interactions from the user of the system or surroundings, e.g. other traffic participants or road conditions. The user is called actor on the system, and is often but not always a human being. In addition, the use-case describes the response of the system towards other traffic participants or environmental conditions. The use-cases are described as a sequence of actions, and the system shall behave according to the specified use-cases. The use-case often represents a desired behaviour or outcome. In the ensemble context a use case is an extension of scenario which add more information regarding specific internal system interactions, specific interactions with the actors (e.g. driver, I2V) and will add different flows (normal &

Term	Definition
	alternative e.g. successful and failed in relation to activation of the system / system elements).

7.1.2. Acronyms and abbreviations

Acronym / Abbreviation	Meaning
ACC	Adaptive Cruise Control
ADAS	Advanced driver assistance system
AEB	Autonomous Emergency Braking (System, AEBS)
ASIL	Automotive Safety Integrity Level
ASN.1	Abstract Syntax Notation One
BTP	Basic Transport Protocol
C-ACC	Cooperative Adaptive Cruise Control
C-ITS	Cooperative ITS
CA	Cooperative Awareness
CAD	Connected Automated Driving
CAM	Cooperative Awareness Message
CCH	Control Channel
DEN	Decentralized Environmental Notification
DENM	Decentralized Environmental Notification Message
DITL	Driver-In-the-Loop
DOOTL	Driver-Out-Of-the Loop
DSRC	Dedicated Short-Range Communications
ETSI	European Telecommunications Standards Institute
EU	European Union
FCW	Forward Collision Warning
FLC	Forward Looking Camera
FSC	Functional Safety Concept

Acronym / Abbreviation	Meaning
GN	GeoNetworking
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GUI	Graphical User Interface
HARA	Hazard Analysis and Risk Assessment
HIL	Hardware-in-the-Loop
HMI	Human Machine Interface
HW	Hardware
I/O	Input/Output
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
ITL	In-The_Loop
ITS	Intelligent Transport System
IVI	Infrastructure to Vehicle Information message
LDWS	Lane Departure Warning System
LKA	Lane Keeping Assist
LCA	Lane Centring Assist
LRR	Long Range Radar
LSG	Legal Safe Gap
MAP	MapData message
MIO	Most Important Object
MRR	Mid Range Radar
OS	Operating system
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
OOTL	Out-Of The-Loop
PAEB	Platooning Autonomous Emergency Braking

Acronym / Abbreviation	Meaning
PMC	Platooning Mode Control
QM	Quality Management
RSU	Road Side Unit
SA	Situation Awareness
SAE	SAE International, formerly the Society of Automotive Engineers
SCH	Service Channel
SDO	Standard Developing Organizations
SIL	Software-in-the-Loop
SPAT	Signal Phase and Timing message
SRR	Short Range Radar
SW	Software
TC	Technical Committee
TOR	Take-Over Request
TOT	Take-Over Time
TTG	Target Time Gap
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to any (where x equals either vehicle or infrastructure)
VDA	Verband der Automobilindustrie (German Association of the Automotive Industry)
WIFI	Wireless Fidelity
WLAN	Wireless Local Area Network
WP	Work Package