



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

C-Roads-Italy Platform

Ex Ante Evaluation

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

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1. Introduction

This Ex-Ante evaluation has been carried out as one of the activities of C-Roads Italy, in order to assess the expected impacts deriving from a jointed implementation of both C-ITS day 1 Services and the Highway Chauffeur system on the basis of the currently available bibliography. This activity is aimed to a first definition of these impacts, mainly in the four impact areas defined in Fot-net 2017 [87] and currently used also within the activities of C-Roads Europe. First, to achieve this objective, in Chapter 2 the available bibliography concerning the Highway Chauffeur system and, more in general, conditional automated driving is analyzed with a particular focus on the impacts that the system alone could entail on the European road network. Therefore, through the paragraphs of Chapter 2, the system is characterized without referring to a specific OEM's product, then the most likely implementation logics in the short and medium term are drawn. Thus, in 2.5, an overview of the expected impacts found in literature is provided, pointing out what are the most acknowledged results and which ones are still a research subject, instead. Then, in Chapter 3, how to evaluate the system's impact on Traffic Efficiency, Environment, Safety and User Acceptance is studied, mainly on the basis of research and sub-research questions. The objective of Chapter 3 is to provide the evaluators across Europe with the tools to design both field tests and modeling works in a coherent and similar way, without losing a necessary grade of freedom needed to account for the local specificities and the differences between different conditional automated solutions. This approach has been privileged to compensate for the relevant uncertainty of the results emerged from the bibliographical review and due to the strong dependence on the parameters that govern both the longitudinal and the lateral behavior of a conditionally automated vehicle. Moreover, it should be noted how the bibliography concerning the jointed implementation of the Highway Chauffeur system and C-ITS Day 1 Services is still scarce of lacking, mainly because both these innovative systems are currently being developed and first experiments on roads are being carried out recently. Then, in Chapter 4, the same approach is applied on the jointed implementation of the Highway Chauffeur system with each Use Case of the C-ITS Day Services judged relevant on the basis of the bibliographical review and of the C-Roads documents produced by the Working Group 2 - Taskforce 2. Both Chapter 3 and Chapter 4 accomplish the objective of an Ex-Ante evaluation, identifying the impacts, but go a little further, highlighting the tools needed to assess each one of them, the most relevant scenarios, the Data judged useful and suggestion on the indicators that should be collected from field tests or obtained from modeling works. Thus, the foundation for the future evaluation activities of C-Roads Italy is laid.

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

2. Highway Chauffeur – bibliographical review

2.1. System overview

The Highway Chauffeur can be defined both as a system and as a function of the vehicle, granted by a level of automation equal to 3 [67]. Longitudinal and lateral control are entrusted to the automation as long as the system is active, meanwhile the driver is generally allowed to engage other activities and to exit the driving loop without compromising safety. The vehicle itself scans the environment, plans the following maneuvers, interacts with the surrounding traffic and, in general, guarantees a safe driving as long as it remains in its Operational Design Domain (ODD). An ODD defines where and when an autonomous driving system is designed to operate, for what type of roadway, speed values, weather or light conditions and so on. As long as the vehicle, by the means of the equipped sensors or of internet communications, perceive itself in the ODD the system it remains engaged and the driver can stay out of the driving loop. As soon as one of the boundary conditions changes or the system itself detects a failure in one of its component, a warning is delivered to the driver that still retain his role as fall-back solution (this role is the biggest difference between L3 and L4 automation as defined by the SAE taxonomy, an L4 vehicle doesn't rely on the driver even if it exits its ODD). Unlike what happens for take over instances in L2 systems, L3 systems guarantee take over times long enough to allow a completely distracted driver to retake situation awareness and understand the reason for the engagement request, thus re-engaging the driving task. Besides, if the driver is not receptive the system must be able to pass to a minimal risk condition which may include slowing the vehicle down and/or reach a safe stop. In [45], the minimum set of information needed to define an ODD is listed:

- Roadway types on which the automated driving system is intended to operate safely
- Geographic area (city, mountain, etc.)
- Speed range
- Environmental conditions in which the automated driving system will operate
- Other domain constraints

A Highway Chauffeur system is designed, in general, to operate on highways, between 0 and 130 km/h, as long as the light conditions and the weather conditions allow the sensors to evaluate the surroundings as precisely and clearly as is needed. It should be noted that this Ex-Ante deliverable doesn't consider an existing system developed by an OEM but examines the technology and its functioning in general on the basis of a bibliographical review, this means

that between OEMs some system's feature can differ from what is stated (for example, a Highway Chauffeur vehicle can be equipped with sensors that allows the automated driving also with light rain while another system can be designed to disengage as soon as it starts raining). Nevertheless, from now on, through the Ex-Ante the system will be referred as "the" Highway Chauffeur and not as "a" Highway Chauffeur, for the sake of the dissertation. Actually, the speed range of 0÷130 km/h includes two automated functions: Highway Chauffeur and Traffic Jam Chauffeur thanks to which the L3 automated driving (longitudinal and lateral control) can be achieved in congested traffic too, for speed values equal to 0÷60 km/h. It is also important to note that, as defined in [19], the Traffic Jam Chauffeur Function might include the lane change functionality and the Highway Chauffeur functionality can include the following maneuvers: overtaking and lane changing. In this Ex-Ante a Highway Chauffeur vehicle (HC vehicle) is considered able to engage both the Highway Chauffeur and Traffic Jam Chauffeur function, therefore, as long as the whole system is mentioned, both functions are going to be taken into account. When the Highway Chauffeur function alone is considered, instead, only non-congested traffic flow scenarios are examined and the speed range of 60÷130 km/h is regarded. An HC vehicle can generally be equipped with Adaptive Cruise Control (ACC), Lane Keeping Assist (LKA), Automated Braking System (ABS) and Front Collision Warning (FCW) to achieve automated longitudinal and lateral control, while to monitor the surroundings a wide array of sensor technologies is employed. For the Highway Chauffeur system to work as intended and to grant an L3 rather than an L2 automation level, an essential role is played by the software and hardware components that perform the driving function without a human actively monitoring the driving environment.

In the following paragraphs an extensive study of the ACC functions and impacts will be carried out, based on the available bibliography. In this system overview is sufficient to explain that an ACC system makes the HC vehicle decelerate when the preceding vehicle on the road travels with a lower speed value and makes the HC vehicle accelerate when the preceding vehicle travels faster than it. In both the situations a desired gap is held between the front of the HC vehicle and the rear end of the preceding vehicle. When no preceding vehicle is detected, the ACC system allows the vehicle to accelerate and travel with a predetermined desired speed value. The Lane Keeping Assist, instead, actively steers the vehicle to keep it in the lane or aligned to a preceding vehicle, this function is possible by the means of the cameras installed on-board able to detect both the preceding vehicle's shape and lane markings (which could also be detected through the LIDAR) when clearly drawn on the road surface.

For an HC vehicle to perceive its surrounding and, for example, to judge if it is still in the planned ODD or to evaluate if a maneuver can be carried out both efficiently and safely, a high number of sensor technologies must be equipped on-board.

An inclusive review of the available sensor technologies has been carried out in [25] and is summarized below to identify the available solutions usually employed for automated driving. Ultrasonic sensors, for example, are employed for short range functions like the car parking assistant, lane keeping and ACC features, moreover they have an operating range of about 2 meters. In terms of image recognitions, camera systems are employed to identify objects (this solution can be hindered by environmental aspects such as weather and light reflection, though). Cameras can accomplish some relevant tasks like road marking detection and traffic signs identification, also machine learning techniques can be employed to teach an AI to recognize and classify certain objects.

“Target of ongoing research is to train systems in a way that they are able to not only detect objects, but also to differentiate with a high accuracy. Exemplary, today’s camera systems in cars are not able to distinguish between a little child and a dog. But in some dangerous traffic situations, it might be essential that the system has the information, if a little child or a dog is unexpectedly crossing the road.” [25]

For night vision, both infrared camera systems and radar sensors can be employed, the latter solution isn’t strongly affected by weather conditions and the operating range can reach 250 m but the limit lies mainly in a limited capability to define the geometry of obstacles. To overcome this drawback, radar solutions are often paired with camera based image recognition. “Radar based systems are applied in automated cruise control, emergency brake systems and collision detection as well as in lane change assistance and blind spot detection systems”. The ACC system employs long-range radio detection and ranging to identify other cars on the road while front and rear end mid-range radar systems (with a range of 30÷150 m) are used in emergency brake assistants and highway assistants (supporting the overtaking maneuvers). To create detailed 3D maps of the surroundings LIDARs can be employed on ranges of more than 100 m, besides, the function is not hindered by light conditions but can find snowfalls challenging.

The information delivered by the mentioned sensors can be compared or integrated both with GPS (or other positioning systems) inputs and with V2X communications. All the information that the system can obtain through these sources must, then, be compared and integrated for it to understand and decipher the environment and accomplish the motion planning function that,

in the end, determines how the vehicle moves on the road. This integration is called sensor fusion and is a fundamental task.

Besides, it is important to highlight how autonomous driving and automated driving are two different concepts. As described in [49], an autonomous vehicle depends entirely on its own sensors and information sources, therefore operates without the aid of Dedicated Short Range Communications with other vehicles or the infrastructure. A fully automated vehicle, instead, is able to execute all driving functions without the driver intervention, also by the means of DSRC in order to understand other vehicles' intentions, for example, or the surrounding environment in ranges broader than its sensors "field of view".

“One could draw the analogy between the autonomous vehicle and a deaf-mute person who can see reasonably well, contrasted with the cooperative vehicle as a person who can hear and speak to others, while also seeing well.”

Similar considerations are expressed in [5]: “An autonomous vehicle typically relies almost entirely on its on-board sensors to make driving decisions, just as humans do. This is in contrast to automated vehicles, which in addition to on-board sensors, they can also take advantage of vehicle-to-vehicle communications, as well as infrastructure-to-vehicle communications”. It should be highlighted how, currently, the European Commission is envisioning an integrated approach that can consider both automation and connectivity in vehicles [103].

Another important function that can be accomplished by DSRC is redundancy. In fact, not only new information helps the automated vehicle in its driving task, a reduction in uncertainties allows the system to face noises in sensors measurements in an easier way, for example. In general, redundancy is one of the main strategies taken into account to face system failures, to the point that [60] mentions redundancies together with safety strategies to handle malfunctions and software errors within the information that should be considered during validation processes and design choices. V2X communications can also be exploited to accomplish maneuvers involving surrounding vehicles in a smoother and safer way, as experimented in [2], for example. Besides, [49] as many other studies, mentions how without V2V communication it does appear unlikely for the progressive advance in automation alone to produce increases in lane capacity and congestion reduction.

A rather relevant subject arises while analysing these possibilities granted by V2X communication. The standards currently defined for services such as C-ITSs are not tuned on the basis of a jointed implementation with automated driving and L3 vehicles such as the HC

one. This means that it is still to be defined if the robustness and reliability of the cooperative messages received by the Highway Chauffeur system are suitable for safety critical applications. Moreover, it is still an open question if the system can receive these messages and validate them without re-engaging the driver in the driving loop (e.g. if the HC vehicle can adapt by itself to the signaled roadworks ahead or if it must receive confirmation by the driver about the received message and the planned maneuvers). This subject will be analysed in the following paragraphs. Generally speaking, an HC vehicle must be able to drive autonomously while in its ODD but, exploiting the information that can be delivered by the means of DSRC, its ODD can be expanded or the take-over maneuver (during which the human driver takes back control of the vehicle) can be carried out in advance, in a smoother and safer way. V2V and V2I communications, in fact, can cover locations beyond sensor line of sight, warn about breakdowns inside the near vehicles or about dangerous maneuvers that other drivers are going to carry out in the surroundings.

A cooperative planning algorithm for the interaction with other road users through V2X communications is explicitly mentioned in [37] as a further research direction in the intelligent motion planning field (together with, for example, the implementation of minimum risk maneuvers in response to failed take-over situations). As long as the perception field is concerned, some of the research areas indicated in [37] are: advanced fusion techniques, quality assessment of the perception system (as a further input for automation) and reliable object recognition and tracking.

In the past years, sensors technologies and hardware and software components have greatly developed, allowing OEMs and all the other stakeholders to equip already existing vehicles with some of the driving support systems mentioned above (L2 vehicles are, in fact, able to drive on public roads on many countries even now). This spread of lower levels of automation on almost every type of road is one of the two possible approach towards the fully automated vehicles. As stated in [26], fully automated driving can be reached, indeed, both by “(...) gradually improving the automation in conventional vehicles so that human drivers can shift more of the dynamic driving task to these systems” and by “(...) deploying vehicles without a human driver in limited contexts and then gradually expanding the range and conditions of their use”. As long as the Highway Chauffeur system is concerned, the most likely approach seems to be the former.

2.2. Expected Benefits, subsisting barriers and legal frameworks

The benefits bound to the Highway Chauffeur system can derive, mostly, both from the possibility for the driver to exit the driving loop and from the automation capacity of removing all the flaws typical of the human driving. An important consideration should be made: while for other systems involving higher automation levels the achievable benefits are often clear and defined from the start (e.g. Truck Platooning), this can't be considered completely true for the Highway Chauffeur system. For example, if it is true that the driving task is probably going to be less demanding and that the time spent each time in the vehicle is going to become productive and/or leisure time with the entrance of the Highway Chauffeur system in the market, it should also be considered that this effect can most likely involve an increased number of kilometres travelled each year (with negative effects both on road congestion, safety and emissions). Making less stressing the time spent on the road can have socio-economic impacts, on medium and long time horizons, that can't be ignored (as, for example, an increased acceptance of long travel times for commuters from home to the workplace and vice-versa). Another subject that can't be ignored while generally speaking of automation is the additional travel demand that could arise from elderly and disabled people, this aspect can be neglected for the Highway Chauffeur evaluation, though, because concerns automation levels equal to L4 or higher. On the other hand, increasing the number of kilometres travelled in automated driving can facilitate the implementation of more environmental-friendly driving styles or the introduction of electric and plug-in hybrid vehicles [43]. In [5] is stated how synergies between automation and electric vehicles are possible because the energy management can be tailored to specifically take advantage of different automation regimes. It is also stated that vehicle automation can potentially impact emissions both reducing road congestion and smoothing the traffic flow. The Highway Chauffeur system can both reduce or increase congestion and improve or worsen the traffic flow depending on the time gaps kept by the ACC for the longitudinal control, though. The time gap is a headway that, depending on the instantaneous velocity, represent the Δt necessary for the front of the following vehicle to be in the exact same spot occupied by the rear end of the leading vehicle in $t = 0$. Being the Highway Chauffeur born mainly as a comfort function for the driver (therefore not meant to ease the congestion on the road or increment lane capacities), the parameters often implemented in the longitudinal control laws are tailored to meet the user preferences and are more conservative than needed from the safety point of view. Having increased time gaps between vehicles and reducing the number of overtaking and lane changing maneuver can surely impact negatively the traffic flow (or not impacting at all as reported in [54]). Lower time gaps can, in turn, hinder User Acceptance towards the Highway Chauffeur system and worsen or prolong the critical market phase once it is allowed on public roads. These

considerations can be made also for the maneuvers of the HC vehicles or for the automation in general: “Initially, AVs will either have no impact, or at worst, they could degrade highway capacity as safety-conscious conservative programming of vehicle speeds and headways reduce vehicle densities and flow” [8]. A more conservative approach is bound both to the existing limits of the automation alone (some of which could be tackled by the use of DSRC, as stated above, and of C-ITS services as will be analyzed later in this Ex-Ante) and to a decreased travel time cost perceived by the drivers which could accept longer trips while enjoying other activities [30]. This, in turn, could lead the drivers to accept a decreased number of overtaking and lane changing maneuvers as long as they can be engaged in secondary activities. Other works found in literature address a possible increase in traffic efficiency (mostly related to a general increase of automation levels and market penetrations) and are, for example, [10, 19, 57] just to name a few.

These kind of impacts are also safety-related, one of the main incentives for higher levels of automation is the shift in authority towards a system more reliable than the human driver thanks to the automation. In fact, it is generally accepted among the stakeholders that an automated vehicle, in order to be deployed on public roads, must be at least as reliable as the human driver (assessed by validation procedures that are still being developed by regulatory agencies like the NHTSA [60]). Generally speaking, from the safety point of view a reduction of human-related crashes can be expected together with the arising of new kind of safety-critical situation bound to automation failures and take over transitions. Human errors contribute or cause about 93% of crashes and can be categorized into recognition, decision, performance and non-performance errors [35, 52]. The Casualty Actuarial Society’s Automated Vehicles Task Force found that 49% of crashes contain at least one limiting factor that could disable the technology or reduce its effectiveness (technology issues or driver behavioral issues) [52]. As long as an L3 system as the Highway Chauffeur is concerned, three main accident causes can be identified: take – over maneuvers (control transition between the driver and the automation and vice versa), environmental-related issues (e.g. adverse weather conditions, erroneous interpretation of other road users’ intentions, etc.) and technology failures. Besides, the most promising benefits that the automation can bring in terms of overall safety are not exploited until the L4 level (in which the driver is completely out of the driving task). There is, in fact, a big difference between L3 and L4 systems (according to the SAE taxonomy): both automated functions are confined in limited ODD but if there is a system failure in the former type of system is the driver that must retake control (given a sufficient take-over time) while in the latter is the vehicle itself that reaches a safe state stopping or reaching the nearest safe spot. The HC vehicle, being still an L3 system,

must grant to the driver sufficient time to re-enter the driving loop and retake control, considering the dynamic nature of the driving environment this could be not always possible though. Enhancement in this task can be achieved through the utilization of Cooperative Intelligent Transport Systems that can alert the HC vehicle in advance about unexpected events on the road ahead (the impacts and possible benefits of the jointed implementation of C-ITS services and Highway Chauffeur systems will be analyzed in the following chapters). The necessity to rely on a conscious driver in order to face sudden changes and exits from the ODD can lead some car manufacturers to incorporate driver engagement monitoring to Level 3 HAV systems [60]. A rather acknowledged percentage in literature is the $\approx 93\%$ of accidents that are considered somehow related to human errors, therefore, by eliminating the human factor from the equation, an increased safety on the road could be achieved (together with an optimization of the vehicle's internal energy management system). Another interesting distinction can be made according to [52] in which safety can be modelled on the basis of the behavior of the driver, the vehicle and the automation functions and of their response in the seconds leading up to a potential crash.

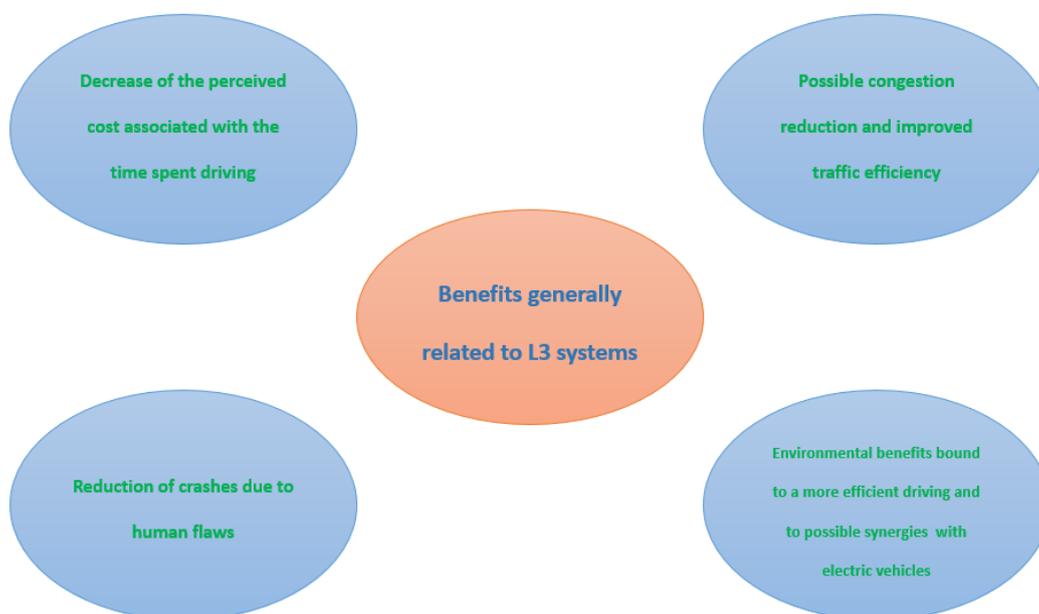


Figure 1 - L3 related benefits

The barriers that still exist for full automation are many and doesn't seem useful to list each one of them in this paragraph. As long as the Highway Chauffeur system is concerned, though, some considerations can be made. Firstly, many of the statements made above about the uncertainty

of the benefits can be repeated as hindrances that still slow down the implementation of such system on public roads. In [14] for example is asserted that automated vehicles could lead to lower or higher road capacities due to increased headways and less assertive behaviors at intersections or, vice versa, due to reduced headways, smoother flows, shorter lag times at signals and fewer crashes. Other foreseen effects of the automation are increased or decreased vehicle miles traveled respectively due to a decreased travel time cost or thanks to a more attractive and efficient ridesharing service. Also an increased pavement distress can be caused by a more concentrated load on the road (vehicles moving more precisely on a specific portion) and, vice versa, an ease on the pavement can be related to smoother vehicle driving.

In the short term, the usage of ACC values less efficient for the traffic flow and more conservative approaches are probably going to happen in order to increase User Acceptance and overcome the mistrust of the buyer in the automation. Besides, a gradual accustoming of other road users towards the HC vehicle can be beneficial and can help build social acceptance and ease the role of politic organizations in promoting higher automation levels. In fact, although the advent of automated driving in the next fifty years is considered inevitable among all the main stakeholders, the road ahead is still long and full of obstacles to overcome and a decisive and coordinated action from the European countries is needed in order to assure an implementation interoperable and optimal for each one of the automated functions that still separates the actual scenario to the fully automated driving. A hesitant and uncoordinated action among European nations, imposed by different degrees of acceptance among the populations, can limit the deployment of higher levels of automation only to the most advanced states in these fields. This disjointed implementation can make the European market of both C-ITS services and semi-automated vehicles ludicrous towards other large markets such as the American or the Asian ones. That situation can easily lead to the imposition of extra-European standards to the Union, which is why it is fundamental to develop a strong and widespread employment among all the countries in Europe.

It should be noted that, on the European level, steps have been made to move in this direction. On December 13, 2016, an amendment to the Vienna Convention on Road Traffic has been promulgated. “This amendment allows the transfer of driving tasks to the vehicle itself, provided that the technologies used are in conformity with the United Nations vehicle regulations or can be overridden by the driver [...] (Act to Amend Articles 8 and 39 of the Convention on Road Traffic of November 8, 1968)” [82]. This allows the deployment on public roads of a system like the Highway Chauffeur one that completely removes the driver from the driving loop and, therefore, retains an increased liability towards what happens to and around it. Moreover, the

EU vehicle approval framework legislation already ensures a special procedure for new technologies and cannot be contradicted by national legislations. New technologies bound to automated driving can already be approved through an exemption and placed on the EU market [103]. It should be noted, though, that despite the existence of some experiments on public roads like the DriveMe pilot program in Gothenburg [14], many countries still lack a national exemption procedure to test partially automated system and to validate them before their market entry.

In Italy the decree SmartRoad has recently been approved as first step in this direction. Nevertheless, a European regulation would be beneficial, enhancing the possibilities for semi-automated vehicles validated in an European country to be able to travel across other countries without interoperability-related or legal issues. Additional work is being done in the following areas [37]: liability and regulatory law, standardization, certification and verification. It is important that these steps are carried out both efficiently and fast because, in order to validate a partially automated system, many kilometres must be driven with the system engaged, this to take into account the very huge number of possible scenarios that could occur on the road.

As stated in [26]: “while desirable, early regulatory action carries risks as well. Prematurely codifying requirements can freeze unrealistic expectations – high or low – into the law in a way that causes the legal framework to lag rather than to lead. Some regulatory flexibility seems desirable, for instance allowing circumscribed uses such as low speed urban operation or motorway platooning before implementing a blanket set of rules”. It is, therefore, essential to identify what are the possible impact bound to the implementation of such systems on the road and their possible interactions with the other road users or with the infrastructure itself. Understanding the most likely implementation scenarios both for the Highway Chauffeur alone or in combination with other innovative transportation systems that share with it similar time horizons is fundamental in order to help policy makers regulate the innovation in the right way, without succumb to the risks described in [26]. This is one of the objective of this Ex-Ante evaluation (the others being to guide the evaluators in designing field tests or modeling works focused on the evaluation of the jointed implementation of the Highway Chauffeur system and of the Day 1 C-ITS services as defined by the C-Roads Platform [69, 70, 71, 72]).

Still, regulations on automated driving systems need to protect public safety from immature or inadequate systems deployed too soon and to encourage innovations that could produce better performing and safer vehicles [53].

To face these challenges, the California state adopted in 2014 a regulation for testing automated vehicles and started in 2017 the formal regulatory process for the deployment of automated driving system on public roads. An important aspect reported in [53] is that the difference between testing and deployment is that “in the latter case the safety of the system must be considered independently of any driver intervention”. This is not the case of the Highway Chauffeur system, though, for which, as mentioned above, the driver is the last fall-back solution. On a more general level, in the USA, the NHTSA is working on an approach to assess both the validation and the safety regarding automated vehicles, on the basis of best practices for the deployment of Automated Driving System from L3 to L5. In [45], for example, 12 safety elements to evaluate safety prior to deployment are defined.

In Europe some adjustments on local legislations have been made too, as discussed in [19]. In [84] is stated that many of the proposals for the ongoing revision of both the General Safety Regulation and the Pedestrian Safety Regulation consider further levels of automation such as Lane Keeping Assist, Intelligent Speed Adaption and Autonomous Emergency Braking. This reflects “(...) a growing recognition of the advantages that the technology can bring, not least in terms of vehicle safety”. To a more local level, the Dutch government, for example, adopted a new legislation to make large scale testing possible for self-driving vehicles on public roads and is working to enable driverless vehicle experiments in traffic. Moreover, in Germany, the PEGASUS project is setup to deliver a definition of a standardized procedure for the testing and the experimenting of automated vehicles (it is important to highlight that within the PEGASUS project, the Highway Chauffeur function will be analyzed in detail [88]). Besides, within the PEGASUS project, a methodology to limit the number of test cases that should be reproduced in simulations or on field tests to assess safety is being developed [100]. Moreover the Finnish legislation allows automated vehicles driving on open roads if a driver is somehow in control even from remote while in Spain an amendment to allow the use of some public roads to test autonomous vehicles is being developed. Moreover, the Spanish road safety authority partnered with Mobileye, a company specialized in Advanced-Driver Assistance Systems. In Greece a framework defining the certification process for automated vehicles and eligible routes for testing has been developed.

In [19] key challenges for the automation are listed, some of which can also be considered for the Highway Chauffeur system, these range from the vehicle related ones to system and services and finally to the society as a whole.

Other possible negative impacts mentioned in [19] are skill degradation of the drivers and their level of trust in the automation (that can be too high or too low). Moreover, completely new liability questions must be addressed to guarantee robust business cases for each one of the stakeholder involved. According to the Motor Insurance Directive, no changes are needed in the directive itself, autonomous or automated vehicles should simply include a third party liability insurance (to consider possible system failures and, thus, the vehicle manufacturer's liability), moreover the European Commission is proposing to fit data recorders inside automated vehicles to determine which one of the two on-board authorities (the driver and the system) retains the control during a crash [103].

Apart from the mentioned barriers, other challenges that the automation must face in the next years concern the transition of control between the driver and the automation:

- Mistrust
- Skill atrophy
- Complacency or primary-secondary task inversion
- Nuisance alerts or multiple and confusing alerts
- Short timeframes available to retake control, the effectiveness of the alerts can fall off quickly when alert times are short
- Increased driver drowsiness and reduced vigilance
- Rapid onboarding, i.e. difficulty reestablishing the driving context after a long inactivity time
- Increased complexity of the system – possible misuse

The above considerations were made in [50] and are derived mostly from the comparison with the aviation field. Many of the issues highlighted in this work possibly involve reduced safety levels and new kind of risks bound to the system automation+vehicle+driver, for example the increased complexity can lead to misuse when the driver doesn't fully understand what action is going to be carried out from the vehicles and why. This issue can arise also when two vehicles negotiate a joint maneuver: "almost anything a driver does in such situations is likely to degrade the automatically computed solution". Another new safety-critical scenario arising from higher levels of automation can be the one in which the drivers doesn't understand what functions remain in his responsibility and what functions are entrusted to the Highway Chauffeur system, instead (this distinction is not carved in stone but is dynamically changing with the surrounding environment and the driving task carried out).

Time horizons

It appears important to report the most common time horizons foreseen by the main stakeholders regarding the deployment of L3 systems on public roads. This way the relevance of both this Ex-Ante evaluation and the activities carried out within C-Roads Italy should be more clear, especially because the deployment of both the Highway Chauffeur system and the C-ITS Day 1 share similar time horizons.

In [37], for example, the roadmap for the automation on highways foresees the start of pilots and large scale demonstrations on public roads from 2016 until 2019 both for the Highway Pilot (an L4 system that carries out both longitudinal and lateral control on highway roads but, unlike the Highway Chauffeur system, doesn't relies on the human driver as fall-back solution) and for the Truck Platooning system. The time window identified for the commercial introduction of the Highway Pilot system is 2022 ÷ 2025, instead. In [103] the availability of both Truck Platooning and Highway Chauffeur is foreseen by 2020. Besides, the impact areas for which an evaluation is recommended in [37] (Mobility, Environmental sustainability, Traffic Efficiency and Safety), are rather similar to the ones adopted in Europe, within the C-Roads activities and, also, in this Ex-Ante. Within the C-Roads activities both the Truck Platooning and the Highway Chauffeur systems will be evaluated in their joint deployment with the C-ITS Day 1 (for which the commercial introduction is foreseen by the European Commission in 2019 [86]) in order to assess the future impacts on the European network and future mobility.

A more recent work that draws a possible timing for the implementation of the Highway Chauffeur system is [19] in which the predictions consider a development path between the years 2018 and 2024, seen as an intermediate step between the established Advanced Driver Assistance Systems and Full automation. Moreover, the roadmap reported in [19] is also the result of a jointed effort with the European initiatives CARTRE and SCOUT [110], founded by the Horizon 2020 program. The aim of CARTRE is supporting the policies of EU Member States in order to ensure that automated transport systems and services will be deployed in a coherent way at EU level. This goal is pursued trough the creation of a knowledge database fostering the exchange of best practices and the design and evaluation of Field Operational Tests. The SCOUT project is focused on both technological subjects and on the study of socio-economic benefits of Connected and Automated vehicles, instead [19].

An aspect that should be highlighted in the ERTRAC roadmap concerns the implementation of digital infrastructures and their role in the development of V2X technologies and solutions. In Italy a step in the right direction was made with the approval of the Smart Road decree [68], it

should be noted how the implementation of digital infrastructures can increase the quality and the quantity of information received by the HC vehicle, thus potentially increasing its ODD or making smoother and safer the take-over maneuvers. A notable mention is the INFRAMIX project [89] that aims to investigate how the road infrastructure (both physical and digital) can support the transition period in which both automated and conventional vehicles will coexist. Other activities towards the digitalization of the infrastructure are being carried out within the UMneo project, for example in the Rheinland-Pfalz the information concerning all roadworks are going to be digitalized and made available [104].

Besides, in [19] an issue is presented, infrastructural elements have a lifespan of several decades which means that the actual infrastructural set-up should be planned considering the higher level of automation. In [29] a milestone is set in 2020 that implies the availability on the market of the Highway Chauffeur system in 2022, instead. In [91] two time windows about market entrance are provided, one concerning conditional automation (equal to 10 years: 2018-2028) and one concerning fully automated vehicles (equal to 20 years: 2025-2045). In [2] a prediction on the possible time horizons is drawn referred to the single automated function, as shown in the image 10. The functions equivalent to the Traffic Jam Chauffeur, lateral and longitudinal control are foreseen to be available in the market by 2025 while more advance functions involving V2X communications and cooperative maneuvers are seen feasible by 2030. However, different trials are already being carried out on public roads across Europe and some technologies are already available on the market, as reported *in* [14].

For example, the GM Super Cruise featured on the 2018 Cadillac CTS has been tested on public roads and accomplishes both lateral and longitudinal control by the means of, respectively, the ACC and the lane following systems. Moreover, this system is equipped to exploit V2V communication. It should be noted that the Super Cruise feature still needs the driver to be engaged in the driving loop and to be ready to take back control at any time. Another ambitious project is being developed by Volvo with the DriveMe trial, initially planned for 2017 but currently delayed to 2021 [78] to face all the issues related to an L4 vehicle like their Volvo XC90. This pilot will take place in Gothenburg, Sweden, on the highways chosen because provided with a 3D map and on which the lane markings are in good condition. The Volvo XC90 are able to access to V2I communication too and exploit the digital map of the road through the Cloud. Tests on public roads were also carried out by the BMW Group on the German highways considered suitable, the evaluation concerned an automated vehicle able to operate up to speeds equal to 130 km/h, while also exploiting a traffic jam assistant system [36].

In 2017 another project started, focused on the implementation and the deployment of an L3 system: the L3 Pilot – Driving Automation, which is planned to last until August 2021 and is based on the FESTA methodology. However, the number of tests and experiments carried out or planned across the European countries is too high to be reported here and is growing fast, in [19] a more complete overview of these project is provided.

On the basis of what has been stated above, a relevant consideration should be made. This Ex-Ante analyses both L3 systems that will likely be available for field tests and L3 systems that will be commercially available and thus will have a relevant impact on areas such as Traffic Efficiency, Environment, Safety and User Acceptance. For the former set of systems it is reasonable to assume that not every application reported in the following paragraphs will be relevant or fully developed. Therefore, what is reported in this Ex-Ante should be seen as the totality (or at least the majority) of the possible applications, functionalities, scenarios and performances potentially achievable in a medium term but not all at once. Thus, it isn't likely that a Highway Chauffeur system will meet all these expectations at the time it will be deployed for field tests, rather it is safe to assume that the first experiences with L3 systems on public roads will be limited in the number of functionalities that will be tested and assessed (both to meet safety standards and to wait for the regulatory framework to be completely defined). Only on a wider time horizon (that it is still difficult to evaluate precisely), when a fair share of vehicles will be equipped with a Highway Chauffeur system, it is possible to assume that more functions and higher performances will be granted by the L3 system. Still, this Ex-Ante evaluation focuses on both the scenarios in order to help future evaluators both to effectively design field tests and to assess the impacts once enough vehicles will be able to achieve L3 driving.

Dedicated Short Range Communications

Between vehicles, information is transmitted through DSRC (Dedicated Short Range Communications), using a 5.9 GHz band and a dedicated IEEE 802.11p. The maximum range achievable is equal to 1000 m, information communicated this way can concern the overall state of the HC vehicle, its driving regime, the traffic ahead, the planned route and possible anomalies, just to name a few. This type of connection follows ETSI (European Telecommunications Standards Institute) standards and must be interoperable between vehicles, independently of the brand, and countries (e.g. cross-border). The HC vehicle doesn't have to be connected but many potentialities are offered by the added information provided through DSRC (both by surrounding vehicles and by the travelled infrastructure through V2I communications).

Moreover, one of the solutions that are being developed currently in the European framework considers the cellular network as possible means of communications, as long as the standard followed is the ITS-G5 one (5G technology is foreseen to become relevant by 2020 [103]). Whatever the mean, in the near future the HC vehicle could be also able to “speak” to the Cloud to receive information both from the Traffic Control Center and other Service Providers. This advancement presents many potentialities that are going to be analysed in the following paragraphs. DSRC can be seen as a precious source of information and the possible applications of cooperative messages paired with a high level of automation (such as L3) are almost countless. It is rather easy to imagine how two automated vehicles, speaking to each other, can pass through a crossroad without bothering the human drivers. Or again, one vehicle entering an highway branch through a ramp could broadcast its need for a gap to the vehicles on the main lane, making the entrance maneuver easier and potentially manageable by the automation itself. Many of these application are going to be mentioned through the Ex-Ante and also analysed, when relevant to the impact assessment. It should be clear, though, that there are still some milestones to be reached before this perfect coexistence between cooperative and automated/semi-automated systems can be seen on public roads. About this topic, one of the outputs of a public consultation carried out within the activities of the CARTRE project (<https://connectedautomateddriving.eu/>) is reported in [110]. In this position paper is clearly stated how “current C-ITS standards do not yet answer the needs of automated driving especially for safety critical functionalities”. Therefore, many of the possible applications reported in the following paragraphs, while technically feasible, won’t be most likely deployed on the first experiences on public roads because the current standards do not yet guarantee the functional safety defined in the ISO 26262 (functional safety defined as part of the overall safety related to the equipment under control, function of the correct functioning of all the safety-related systems and of the external risk reduction facilities).

“Higher levels of automation will require reliable and low latency connectivity to a vehicle cloud or back end to operate safely. Only on this basis, Automated Driving “service suppliers”, most likely OEMs, will take the responsibility of the driving task. Would this connectivity fail, the vehicle should ask the driver to pay attention to the road situation e.g. L2.” [110]

Another relevant document on the subject is [112], focused on the different approach that should be followed while assessing the safety of a cooperative vehicle rather than a traditional one (for which the adopted vehicle centric perspective is already suitable for the safety assessment).

According to the authors, this shift in perspective, as first consequence, implies that an additional severity class should be considered because a cooperative system involves more than one vehicle. Knowing that cooperative applications (such as V2V messages) interacting with L3 systems should accomplish higher levels of safety integrity (referred to as ASIL), the approach suggested in [112] is the decomposition of safety requirements among redundant elements, each one with a less severe ASIL requirement. Another advantage of the cooperative approach rather than the vehicle centric one is a more inclusive HARA (Hazard Analysis and Risk Assessment), one of the steps defined in the ISO 26262 for the safety assessment. In fact, considering all the vehicles (and external sources of information) allows to identify also possible hazards arising from failure of the cooperative system itself (hazards that would be missed while considering only the vehicle itself).

“In the vehicle centric perspective we must assume that whatever is specified for V2V communication will be sufficient for achieving. However, there is no way to let the specification of the V2V communication (including choice of protocols for assuring consensus and consistency) become a part of a safety case showing that reasonable failures in the V2V communication will not violate any safety goal. On the other hand, in the cooperative perspective, the safety requirements allocated on the V2V communication gives a reason to investigate what kind of redundancy that is needed to enable safety arguing.”

2.2. Longitudinal control

As stated in 2.1, one of the main functions carried out by the Highway Chauffeur system is the longitudinal control, accomplished by the means of the Adaptive Cruise Control (in literature the same system can be referred as automatic or advanced cruise control or also intelligent cruise control and intelligent adaptive cruise control, as stated in [32]). It should be highlighted from the start an important difference between the ACC-equipped vehicles and the CACC-equipped ones (such as in Truck Platooning, object of another branch of the C-Rads Italy activities). While the former system uses only on-board (long range radar) sensors to determine the distance from the HC vehicle to the preceding vehicle and the speed difference between them, the latter exploits DSRC to broadcasts accelerations and decelerations value and guarantees shorter headways between, for example, two trucks platooned. Therefore, an HC vehicle driving on a highway road can take the longitudinal control from the driver and accelerate or decelerate to reach a targeted speed value that can be both a cruise value in free flow conditions (up to 130 km/h) or a lower speed value needed to keep a predetermined headway from a preceding

vehicle. In most solutions the driver pre-sets the target speed in free flow and a preferred time gap, for example by the means of a lever near the steering wheel.

Leaving the choice of the functional parameters to the drivers caused in literature a relevant uncertainty about the potential impacts on the traffic flow. If it is true, in fact, that the ACC could guarantee safety even with reduced time gaps, compared to the one needed to the human driver, it is also showed for example in [54] that many drivers are comfortable with time gaps similar to the one they chose when driving manually (actually nullifying the potential benefits of the ACC on road capacity). This uncertainty usually leads to more conservative approaches also in modeling works such as, for example, [90]. Nevertheless, it can be stated that the use of the ACC system can reduce the perception and reaction times while still maintaining a certain lag in braking which instead disappears when the CACC is considered, as reported in [14]. Another effect of the ACC concerning the impact areas of Traffic Efficiency and Environment is the flow stabilization with respect to perturbations and to oscillation waves caused near a bottleneck section (before reaching the congested state of the traffic flow) [16], accomplished by the means of the Traffic Jam Chauffeur function too. Another potentiality of the Highway Chauffeur system could lie in more efficient maneuvers, for example near ramp areas, but again these benefits are dependent on the aggressiveness rather than the conservativeness of the implemented algorithm. In this paragraph the most relevant works about longitudinal control are going to be analyzed, both regarding the Highway Chauffeur implementation on public roads and from the perspective of a jointed implementation with the Day 1 C-ITS mainly aimed at speed control, shockwave damping and traffic management. Please note that, while evaluating the jointed implementation, a relevant hypothesis is made:

Cooperative messages received by the Highway Chauffeur system are considered validated and exploitable by the system in order to adapt its driving behavior.

This hypothesis is not necessarily true, considering that the requirements currently defined for cooperative messages do not meet all the standards defining functional safety of an automated vehicle (as defined in the ISO 26262 - ASIL B) yet. This limitation is especially burdening for safety-critical applications while, for not safety-critical application, lower ASIL levels could be considered sufficient, this double ASIL certification could be achieved without additional costs only if the two domain are isolated.

Kesting, A., 2008. Microscopic Modeling of Human and Automated Driving: Towards Traffic-Adaptive Cruise Control, Technische Universität Dresden (Germany).

A first relevant work in this field is [32], aimed both at defining a microscopic traffic flow theory to investigate emerging collective traffic dynamics and at introducing a traffic-adaptive control strategy for ACC-equipped vehicles. Generally speaking, the times characterizing the collective dynamics and the stability of the traffic flow are identified as: the delay caused by the human finite reaction time, the time lag due to a finite speed adaptation needed to reach the desired velocity and the numerical update time. If an HC vehicle is considered, the first and last time intervals can be reduced or neglected, limiting short-wavelength local instabilities. In this work a comparison is carried out between a baseline scenario and the one that considers the implementation of the automated longitudinal control.

“Applying the concept to the IDM¹ allows us to carefully distinguish between reaction time, adaptation time and update time. By means of simulation, the role of each of these times will be investigated with respect to instabilities of traffic flow. The analysis of the model enables us to understand and to assess the impact of generically human factors on the driving behavior. This research question will also be relevant against the background of the operational differences between human drivers and automatically controlled vehicles by means of ACC.”

The ACC system considered in this work allows the driver to set a desired speed and a safety time gap that can range from 1 s to 2.5 s, the most limiting characteristics of this work when compared to the Highway Chauffeur system are:

- The lateral control entrusted to the human driver
- The creation of cut-in gaps for other vehicles entering the lane still entrusted to the human driver
- The absence of the Traffic Jam Chauffeur function and the ineffectiveness of the ACC under 30 km/h

Different strategies concerning the modeling of the ACC system are planned in this work: an acceleration strategy to reach the target velocity, the braking strategy to approach other vehicles or obstacles and the car-driving strategy to maintain a safe distance behind another vehicle. The parameters of the model are: the desired velocity, the preferred time gap, limited acceleration

¹ Intelligent Driver Model

and deceleration values and a reaction time. Because this Ex-Ante evaluation wants to assess, where possible, the impact of the Highway Chauffeur system, the sections of [32] concerning the human maneuvers and/or reaction times won't be reported, for the complete dissertation please refer to the work of Kesting.

In assessing the impacts related to the ACC system, the author considers the microscopic modeling approach to be the most effective to evaluate the impact of the driver assistance system on the collective traffic dynamics. In order to evaluate the impacts of the automated longitudinal control, the chapters regarding the dynamic traffic conditions and traffic-adaptive ACC modes are going to be analysed while the microscopic traffic dynamics won't be presented in depth. It is important to report, though, how the hypothesized IDM responds to perturbations in the traffic flow. When the first vehicle brakes, the small perturbation travels further downstream until, after a while, it increases and propagates itself upstream. This happens because of the time delays that the human drivers need to react to the braking. The following vehicles, in fact, need some time to respond and decelerate. Therefore, when the vehicle is slowed down to the reduced velocity imposed by the first vehicle, the actual distance is lower than the safe one and additional braking is necessary, leading to lower speeds compared to the one in the vehicle that first braked. The human driving can count on the human ability of routinely scanning the traffic situation several vehicles ahead, while interpreting the surroundings and anticipating near future situations, which is an advantage when compared to the Highway Chauffeur system. Once defined the simulation parameters both for the human driving and the automated longitudinal control, the ACC system was modelled to be a traffic assistance system in which vehicles are able to automatically adapt the operational parameters to improve traffic flow and road capacity when compared to the baseline scenario (human driving). This is achieved by the introduction of a strategic level in which the traffic situation is locally determined and the ACC parameters are updated to achieve improved traffic flow conditions. Thus, on the operational level the input quantities influence the ACC functioning and the values of the time gap, speed and speed difference with the preceding vehicle are updated. When the flow is stable the parameters are the ones that the driver set as comfortable.

The strategic level considers five traffic situations:

- Free flow conditions
- Approaching an upstream congestion front
- Congested traffic
- Leaving the downstream congestion front

- Passing infrastructural bottleneck sections (work zones are explicitly mentioned, which is relevant for the evaluations carried out in the next chapters).

It is important to highlight how the author considered the use of V2I and V2V communication to enhance the detection of the traffic situations around the ACC-equipped vehicle. The driving behavior resulting from this kind of ACC implementation must be both comfortable for the drivers (which means larger gaps and lower accelerations) and able to enhance the traffic flow (which means smaller time gaps and larger accelerations). These conflicting needs are met by varying the gaps and acceleration values according to the surrounding traffic situations, following the below functioning logic:

- In free flow condition the ACC parameters are the one previously set by the driver
- Approaching the jam front, the objective is to increase safety reducing speed differences between vehicles and starting earlier braking maneuvers (which is also more efficient for the overall traffic flow)
- Congested traffic, the ACC values are reverted to the pre-set ones, it is important to note that this work doesn't consider the implementation of the Traffic Jam Chauffeur functionality
- Downstream the jam front, to increase the dynamic bottleneck capacity accelerations are increased and time gaps are decreased
- Bottleneck sections, time gaps are decreased to locally increase the capacity

Thus, to assess the impacts of this strategy, the ACC is modelled through a car-following model that is collision-free and physically possible. Transitions between traffic situations are carried out without oscillations and in a comfortable way, the parameters required are at least the target speed and the desired time gap chosen by the driver. Without exploiting possible DSRC, the traffic situations are detected by the vehicle on the basis of the locally available velocity time series data of the ACC equipped vehicles and of the preceding one (measured by the radar sensors). As can be easily understood, the free flow condition is characterized by a high average speed value while the congested one by low average ones. Upstream and downstream congestion front are detected, instead, on the basis of changes in the speed values. The localization of bottleneck sections cannot be accomplished without external information about the infrastructure and its state (that can be provided by a digital map database, as mentioned by the author), this introduces the need for digital infrastructures and the update of the existing ones, at least on the main corridors in the short term, in order to support the deployment of

automated vehicles from L3 to L5. As mentioned above it is clear how, for a HC vehicle to adapt its acceleration and time gap values on the basis of a V2X message, said message must have certain robustness and latency attributes (not yet fully guaranteed by the current standards [110]). For example, if a speed limit is transmitted through I2V from the Traffic Control Center to an L3 vehicle and is exploited to tune the cruise control, the communication must meet the requirements of a certain ASIL level.

With this simple approach multiple traffic situations can be met simultaneously, the author derived from the simulations the most efficient decision order: downstream front → bottleneck → traffic jam → upstream front → free traffic. This transition obviously cannot be carried out instantaneously and must also account for time delays, which means that the adaptation of accelerations and time gaps should start in advance to be smoother. Thus, a prior knowledge of the downstream traffic situation would be beneficial to this ACC implementation and could be achieved, as mentioned before, exploiting V2V and V2I communications (additional benefits could be derived by the signaling of temporary bottleneck such as accidents, for example, a scenario that is going to be studied in Chapter 4).

Once defined the operational framework of the ACC-based traffic assistance system, as defined by the authors, simulations were carried out in order to assess the impacts of a certain number of ACC-equipped vehicles in the traffic flow (it should be noted that these considerations could be extended to the HC vehicles and their impacts bound to a more efficient longitudinal control achieved thanks to the automation). The results obtained in [32] from the simulations can be considered only as qualitative for an HC system as hypothesized in this Ex-Ante (where the lateral control is also automated and the Traffic Jam Chauffeur can be used to ease the congested traffic flow). Below the parameters adopted for the IDM and the human driving are reported, as assumed in [32].

- Desired velocity: Car = 120 km/h; Truck = 85 km/h
- Safety time headway T: Car = 1.5 s; Truck = 2 s
- Maximum acceleration: Car = 1.4 m/s²; Truck = 0.7 m/s²
- Desired deceleration: Car = 2 m/s²; Truck = 2 m/s²
- Jam distance: Car = 2 m; Truck = 2 m

The detection time of the radar in an ACC-equipped vehicle is considered negligible, the system determines the instantaneous acceleration that must be adopted as a function of the actual speed value, of the time gap and the speed difference between the own vehicle and the preceding one. Once defined the control laws characterizing both ACC-equipped vehicles and

human driven ones, simulations with an on-ramp bottleneck were carried out. No numerical results will be reported in this Ex-Ante, considering the strong difference between ACC-equipped vehicles and HC vehicles, but qualitative results can be commented to assess the kind of impacts expected with automated longitudinal control:

- An increased portion of ACC-equipped vehicles leads to a reduction of the traffic jam
- A penetration rate equal to 10% of ACC-equipped vehicles is enough to improve the traffic flow significantly in three-lane simulations
- A portion of 30% of ACC-equipped vehicles is not enough to avoid the traffic jam formation in a one-lane scenario
- The maximum flow in free traffic increased with a 25% penetration rate of ACC-equipped vehicles, the breakdown of the traffic flow is retarded or avoided and the increased outflow leads to a faster relieve of traffic congestion

The results listed above consider the ACC-based traffic assistance system, not a simple ACC tailored on the comfort of the driver. Moreover, rather high values of decelerations are assumed and can be difficult to obtain in reality due to both User Acceptance and Safety-related aspects. Even if that doesn't meet the OEMs' strategies, it can be assumed that, at least in some situations (such as roadworks, accidents zones, heavy congestion, etc.), an HC vehicle could receive suggestions through V2X communications and adapt accordingly its driving regime. In [32], to evaluate the performance of the road system instantaneous and cumulative travel time were considered as parameters, together with the flow-density relationship.

- Cumulative travel times decrease consistently as long as the fraction of ACC vehicles increases
- Cumulative travel times standard deviation decreases as long as the ACC vehicles increase in the traffic flow

Another set of simulations was carried out considering an uphill gradient bottleneck and resulted in similar results about road capacity and traffic efficiency, a reduction in queue lengths was observed too.

Other results worth noticing concern the gain in maximum free flow which, for a 50% penetration rate of the ACC, is equal to 16-21%, for a portion of ACC equal to 20% the maximum free flow can increase by about 7% instead. Moreover, the safety time gaps appear much more impacting than the maximum acceleration.

After a traffic breakdown, the dynamic capacity increases thanks to the proposed driving strategy and, mainly, to the regime "downstream jam front", again both increasing the time gaps and the

maximum accelerations affects positively the traffic flow. Another relevant conclusion is that the downstream flow state is not detected by the vehicle sufficiently in advance and the ACC action results ineffective due to this delay, the dynamic capacity is not incremented in this case if V2X communications or digital maps are not employed.

Shladover, S., Su, D. And Lu, X., 2012. Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow.

Another relevant work that explored the potential impacts of the ACC system on Traffic Efficiency and highway capacity is [54], in which the authors compared the possible benefits with the ones obtained by the means of Cooperative Adaptive Cruise Control (which won't be reported in this Ex-Ante because not directly related to the Highway Chauffeur system). Besides, some objection to the assumption made generally about the ACC implementation are made, such as the optimistic car following model employed to dampen traffic disturbance for the ACC driving and the use of the IDM car following model which incorporates, in the authors' opinion, unrealistically hard braking in response to vehicles that cut-in). Also, the adoption of simple first-order dynamic responses for the ACC car following is considered more stable than the actual responses of ACC systems which have substantial transport lags depending on the limitations of their sensors. Thus, the control algorithm adopted in this work is designed as follows.

Two modes are considered: speed control and gap control, the former is activated when the preceding vehicle is further than 120 m and the latter when the spacing is smaller than 100 m (both distances were defined based on highway speed values). Between 100 and 120 m the algorithm keeps the actual control strategy to avoid hysteresis.

The speed control law is $v_e = v - v_d$ where v_e is the speed error, v the instantaneous speed value and v_d the desired speed value (set by the driver or bound to the road speed limit). The acceleration by speed control is equal to $a_{SC} = \max(\min(-0,4 v_e, 2), -2)$ where +2 and -2 m/s^2 are the maximum acceleration and deceleration achievable by the vehicle under the ACC control.

In gap control three more boundary are imposed:

- $s_d = T_d v =$ desired spacing. T_d is the desired time gap
- $s_e = s - s_d =$ spacing error. s is the current spacing and s_d the desired one
- $a = \max(\min(\dot{s} + 0,25 * s_e, a_{SC}), -2)$. a_{SC} is the acceleration by speed control

With these control laws the authors simulated a one-lane freeway, the desired headway for manual driving is equal to 1.64 s and, for the ACC-equipped vehicles, the following distribution is assumed: 2,2 s for 31,1% of the ACC-equipped vehicles, 1.6 s for 18.5% and 1.1 s for 50.4%.

The results from the simulations showed that the percentage of vehicles with automated longitudinal control in the traffic flows doesn't really affect the capacity. The flow, in fact, remained in a range of 2030÷2100 veh/h that, compared to the baseline scenario with only manual vehicles, doesn't change much (2018 veh/h). The authors considered this finding a consequence of the time gaps hypothesized for the ACC-equipped vehicles similar to the ones a human driver would keep.

Similar considerations appear in [97], a work in which a field test evaluating the commercial ACC and the resulting string stability/instability is analyzed. Again, the system considered is tailored on driver comfort and from the results seems that an increased ACC market penetration can cause a less stable traffic flow. In fact, the ACC tested in [97] accounted for delays bigger than the ones characterizing human driving and resulted in severe oscillations (in one braking maneuver a deceleration of 1 m/s^2 from 30 to 26 m/s^2 performed by the leading vehicle, in a platoon of five ACC equipped vehicle, resulted in a brake of the last vehicle equal to 20 m/s). The authors consider this difference from the modeled results as a consequence of "(..) the response delays associated with ranging sensor signal processing and vehicle actuation" that rarely are considered in modeling works.

Stern, R.E., Cui, S., Delle Monache, M.L., Bhadani, R., Bunting, M., Churchill, M., Hamilton, N., Haulcy, R., Pohlmann, H., Wu, F., Piccoli, B., Seibold, B., Sprinkle, J. And Work, D.B., 2018. Dissipation of stop-and-go waves via control of autonomous vehicles: Field experiments

A study that tries to exploit the properties of automated vehicles to ease traffic congestion is [57]. It doesn't refer explicitly to the Highway Chauffeur system but considers the effect of an automated vehicle whose speed is controlled externally or by the means of a well-tuned algorithm defining longitudinal control. The study is focused on the damping of the phantom traffic jams caused not by an external event but by the internal flaws of the human driving.

"Recent advancements in vehicular automation and communication technologies provide new possibilities and opportunities for traffic control in which these smart vehicles act as Lagrangian actuators of the bulk traffic stream. When a series of adjacent vehicles on a roadway are connected and automated, it is possible to form dense platoons of vehicles which leave very small gaps."

Therefore, the authors examined the ability of connected and automated vehicles to dissipate stop and go waves without changing how the surrounding human-driven traffic operates. This

subject is analyzed through a closed ring test (chosen to simplify the experimental setup) in which more than twenty vehicles drive, one of which is autonomous-capable and can run more than one longitudinal control law.

The control strategies planned and compared are: fixed averaged velocity (FollowerStopper controller) and proportional-integral controller with saturation. The first one allows the automated vehicle to follow the preceding one as closely as safely possible, relying on on-board sensor measures, while the second strategy allows to saturated small and long gaps to simultaneously avoid collisions and slowing down the traffic. The desired velocity held by the controller can be based on the information derived from the on-board sensors or can be broadcasted from an external observer depending on the control strategy adopted. The autonomous vehicle employed was the one developed in the University of Arizona (CAT vehicle) that can transition between manual and autonomous speed control, only the longitudinal control can be automated while a trained human driver must control the steering wheel all the time. The CAT vehicle is the only one controlled to dampen the shockwaves arising in the traffic flow, a choice made to reproduce a low penetration rate and assess the potentiality of the automated driving in the short term. 360 degree cameras and OBD-II data loggers were employed to collect data from each experiment. The CAT vehicle begins each experiment in manual mode, the experiment consists of six phases: Setup, evacuation, initialize, drive, stop and conclusion. The basis of the work can be considered rather similar to the one followed in [32]: the overall flow can be stabilized by the means of a subset of vehicles driving with a smooth driving profile (varying on the basis of the surrounding traffic conditions).

“One possible way to create a smooth driving profile is to follow the average speed of the vehicles ahead, which drive faster than the average speed before a stop-and-go wave, and slower than the average speed during the wave. By simply driving at the average speed, a vehicle covers the same distance in the same amount of time, but with less acceleration and breaking.”

The logic mentioned above is the one characterizing the two control laws tested by the authors. In both the adopted laws, the CAT vehicle tracks its own speed v^{AV} and the spatial gap from the preceding vehicle Δx . Thus, the speed held by the preceding vehicle is estimated by the CAT vehicle as $v^{LEAD} = v^{AV} + \Delta v$ where $\Delta v = \frac{d}{dt} \Delta x$. With these parameters the longitudinal controller can set a desired speed value that can be employed to stabilize the traffic flow. This is achieved

defining the optimal value of commanded speed that is finally passed to the low-level controller of the CAT vehicle and translated into acceleration or deceleration values.

The FollowerStopper controller follows an operational logic rather similar to the ACC one, the desired speed value is commanded as long as the spatial gap ahead is wide enough, while a lower speed value is implemented whenever safety requires. Three spatial regions have been defined by the authors:

- A safe region where the speed is equal to the desired one
- A stopping region where a null value of speed is commanded
- An adaptation region where an average value is commanded, based on the speed of the preceding vehicle and the CAT desired value.

The longitudinal control law is therefore defined as follows.

$$\begin{aligned}
 v^{CMD} &= 0 \text{ if } \Delta x \leq \Delta x_1 \\
 v^{CMD} &= v \frac{\Delta x - \Delta x_1}{\Delta x_2 - \Delta x_1} \text{ if } \Delta x_1 < \Delta x < \Delta x_2 \\
 v^{CMD} &= v + (U - v) \frac{\Delta x - \Delta x_2}{\Delta x_3 - \Delta x_2} \text{ if } \Delta x_2 < \Delta x \leq \Delta x_3 \\
 v^{CMD} &= U \text{ if } \Delta x_3 < \Delta x
 \end{aligned}$$

Where U is the desired speed value and $v = \min(\max(v^{lead}, 0), U)$ can be both the preceding vehicle's speed value or the desired speed value. Δx_i are the values defining the three spatial region defined above and conditioning the controller behavior. Once defined the longitudinal control law, the experiment was carried out varying the value of Δx_i (x_i is the position) and of the deceleration rates.

The PI with saturation controller is based on the estimation by the CAT vehicle of the preceding vehicle's average speed, instead. If this average speed value is kept by the CAT vehicle, as soon as stop and go waves arise, the gap widens when the preceding vehicle accelerates and closes itself when the preceding vehicle decelerates. The average speed value is calculated on the basis of the measurement of the preceding vehicle speed over a large enough time horizon and a commanded velocity for the low-level controller is determined consequently, until the spatial gap remains wide enough to guarantee safety but not so large to encourage other vehicles in performing lane changing or overtaking maneuvers in real-life scenarios (this additional feature is defined saturation by the authors). Therefore, the controller computes the desired speed value averaging the speed kept by the CAT vehicle itself over a time interval.

$$v^{target} = U + v^{catch} * \min \left(\max \left(\frac{\Delta x - g_l}{g_u - g_l}, 0 \right), 1 \right)$$

Where v^{catch} is a speed value higher than U and allows the CAT to catch up with the preceding vehicle when the spatial gap exceeds the lower threshold g_l (equal to 7 m). g_u is the upper threshold for the spatial gap. Then the authors derived the following control law:

$$v_{j+1}^{cmd} = \beta_j \left(\alpha_j v_j^{target} + (1 - \alpha_j) v_j^{lead} \right) + (1 - \beta_j) v_j^{cmd}$$

Where j is the time step and α and β are weights that take into account the spatial gap tuned in a way that for short gaps only the preceding vehicle's speed matters while for large gaps only the desired speed value is averaged with the commanded speed value.

Once defined both control laws, the experimental results were compared using metrics able to describe the traffic flow such as the spatially averaged instantaneous velocity, the speed standard deviation of all the vehicles or the throughput of traffic. Fuel consumption of each vehicle over a time interval and the braking events were considered too.

The FollowerStopper control law resulted able to dampen the effect of the shockwave, lowering the magnitude of the oscillations from the mean in the velocity profiles. Also, increasing the desired speed value until it matches the average traffic speed leads to the best performance of the controller which resulted in lower speed standard deviations, lower fuel consumption and less braking events (respectively, reductions equal to 80.8%, 42.5% and from 8.58 braking events per vehicle per kilometer to 0.12 per vehicle per kilometer). The traffic throughput increased too, by 14.1%.

From the reported results it should be noted that the traffic average speed during the experiment was equal to 7.5 m/s, exceeding this value made the automated vehicle generate a shockwave itself, which was partially reabsorbed once returned to the optimal speed value. Besides, the authors highlighted how the fuel consumption recorded during the experiment with the FollowerStopper controller was the lowest achieved among all the experiments. Using the PID controller with saturation resulted in a substantial reduction of the shockwaves, the benefits are similar to the ones achieved with the FollowerStopper controller: the speed standard deviation is reduced by 54,7%, fuel consumption by 27,9%, the rate of excessive braking by 74,4% and the throughput by 2.5%. This time, the average speed of the traffic is reduced, though. It is important to highlight that this controller doesn't require external information but can function

only with the information directly measured by the CAT vehicle itself, unlike the FollowerStopper controller.

Both the solutions involved relevant benefits both concerning Traffic Efficiency and the Environment, this work suggests that an automated vehicle with a proper longitudinal control law can control or affect the flow of at least 20 manual driven vehicles. Moreover, a decentralized approach aimed at shockwave damping can improve most contemporary traffic control strategies such as ramp-metering or variable speed limits. These possibilities will be analysed in depth in the following paragraph, especially when considering a jointed implementation with use cases such as Dynamic Speed Limit and the use of V2I communications.

Delis, A.I., Nikolos, I.K., M.Papageorgiou., 2015. Macroscopic traffic flow modeling with adaptive cruise control: Development and numerical solution.

In [16] the effects induced on the traffic flow by an ACC-equipped vehicle responding to a change of speed in the preceding vehicle are analysed. In order to do so, a macroscopic gas-kinetic traffic flow (GKT) model is presented, two set of simulations were carried out by the authors, the first one is for a flow on a circular homogeneous freeway (in the same fashion of [57]) while the latter considers also an on-ramp bottleneck.

The following assumptions were made during the simulations:

- The ACC penetration rate is equal to 100%
- All the vehicles have the same mechanical characteristics
- All the equipped vehicles have the same parameter values for the ACC
- No lane changing maneuvers are carried out

It should also be noted that with this framework, the CACC impacts were analysed in this study too but will not be reported in this Ex-Ante because judged less relevant for an HC vehicle.

The GKT model is based on microscopic models and is considered able to describe realistic traffic flows and hysteretic phase transitions to congested states near bottleneck sections. Due to the model complexity, in this Ex-Ante only considerations about the parameters and its functioning will be reported, please refer to [16] for the full model description. The modelled ACC system makes the vehicle drive with the maximum speed set by the driver when no preceding vehicle exist in the range covered by the sensors (or exist but drives with speed values higher than the one chosen by the driver). This travel mode is called speed control mode. If a vehicle is detected by the sensors and its speed is not too high, the ACC-equipped vehicle maintains an equal speed value at a specified distance. This travel mode is called gap control mode, the

transition between it and the speed control mode (and vice versa) should be as smooth as possible. An important feature of the model is the ability to consider explicitly the held time-gap, letting the evaluator change with ease this value and simulate different ACC flows and different dynamic behaviour. Besides, in this work a more rigid distinction between gap and headway is taken into account: a headway is calculated between the front bumper of the preceding vehicle and the front bumper of the following one while a gap is calculated between the rear bumper of the preceding vehicle and the front bumper of the following one. A constant Time Headway spacing policy was adopted in the modeling framework because, being a linear function of the vehicle's speed, feels more natural to the passengers of the ACC-equipped vehicle. Moreover, the authors introduced in the GKT traffic flow model a relaxation term able to satisfy the time/space-gap principle of ACC systems, this term is not considered for densities below a threshold ρ_{acc} when the drivers set their maximum speed as in manual driving but, in the region around ρ_{acc} a smooth transition in control takes place in favour of the ACC controlled situation. ρ_{acc} is the density for which the ACC controller influences the driving style and is equal or lower than the density values ranging between free flow and congested traffic state.

The transition is described by the means of the following Fermi function:

$$F(\rho) = \frac{1}{2} \left[1 + \tanh \left(\frac{\rho - \rho_{acc}}{\Delta\rho} \right) \right]$$

During the gap control mode, instead, a constant time gap T^* is set on the basis of its effect on the desired density $\rho^* = \frac{1}{\frac{1}{\rho_{max}} + T^* u^*}$. The denominator is the desired space headway, $1/\rho_{max}$ represents the length of the vehicle and u^* is the speed kept by the preceding vehicle.

Thus, with this model, a traffic flow driving in a ring of circumference of $L = 10$ km was simulated and perturbations arose, leading to instabilities once the traffic flow reached given values of density. The first simulated scenario is called localized cluster: in an unstable traffic flow a perturbation generated a single density cluster of manually driven cars, the perturbation first travels downstream but once has grown it starts to propagate upstream. If an ACC system is implemented, with a relaxation time equal to 1 s, the traffic flow becomes stable and uncongested traffic is obtained even with an initial perturbation travelling downstream. Therefore, the traffic flow throughput results increased. It should be also noted that the authors chose a time gap of 1.2 s for the ACC, a value judged more conservative but also more realistic, but highlighted how a value of 0.8 s could be implemented too, reflecting a more aggressive driving behaviour in the ACC-equipped vehicles. The second scenario simulated is the stop-

and-go waves one in which, increasing the density, a certain number of traffic jams arise across the test ring when only manually driven vehicles are considered.

In the simulations considering also the presence of ACC vehicles in the traffic flow, still an unstable regime is obtained but the stop and go phenomenon is dampened and the congestion is delayed or completely avoided. Besides the traffic flow rate along the test ring increases in this scenario too.

The last scenario considered is called suppression of a traffic jump where a metastable traffic flow is obtained. This means that the traffic flow is nonlinearly unstable when facing a perturbation exceeding a certain threshold but stable otherwise. In this scenario the presence of ACC-equipped vehicles reduces quickly the initial perturbations and potentially avoids the instability.

The second set of scenarios simulated was designed to analyse the dynamics of the traffic flow near on-ramp areas. The main difference is that, in this kind of scenarios, the dynamics are controlled by the inflow for the free flow state and by the dynamic bottleneck capacity in congested state. The infrastructure-related parameters varied by the authors were, for example, the freeway ramp length, the ramp inflow or the initial traffic density. In each simulation, a perturbation was introduced by linearly increasing the ramp flow for 2.5 minutes. Different congested states for manual traffic were obtained this way and the impact of the ACC system was analysed.

In this case the most relevant scenario is represented by triggered stop-and-go waves in which a breakdown in traffic close to the on-ramp area happens and the bottleneck is activated by the perturbation travelling upstream. From the simulations appears that the presence of ACC equipped vehicles ease the traffic breakdown and increases the local capacity.

Near the on-ramp areas, simulations taking into account a congested initial flow were conducted too. In these simulations only the ramp inflow was varied and no perturbation was imposed and no computational parameter was varied. In this kind of scenarios, the ACC traffic proved to be able to produce an uncongested flow downstream the ramp (increasing the flow both upstream and downstream) and to reduce the homogeneous congested traffic upstream, depending on the flow value on the ramp.

“From the numerical results, we can conclude that, by applying ACC [...] systems, the flow becomes stabilized with respect to on-ramp perturbations (temporary inflow peaks) and all oscillation waves caused near a bottleneck can be eliminated for densities on the uncongested side of the fundamental diagram”

It should be highlighted how these results were obtained thanks to the adaptation of the GKT model performed by the authors. Therefore, it can be concluded that a certain quantity of ACC-equipped vehicles in the traffic flow can enhance Traffic Efficiency and Environmental aspects as long as the longitudinal control law is tailored both to meet the human driver needs and to perform reduced spatial gaps and more efficient accelerations and decelerations maneuvers.

Mathijs Huisman, 2016. Impacts of (Cooperative) Adaptive Cruise Control on Traffic Flow. A simulation case study on the effects of (cooperative) adaptive cruise control on the A15 highway.

In [102] a research effort was carried out by the author to assess the impacts of CACC and ACC systems. This study is composed not only by a well-designed modeling work, source of interesting results, but also by a wide bibliographical review on the basis of which the most used parameters were derived. In the following, only the ranges are reported for these values:

- Desired time gaps: $1 \div 2,2$ s
- Comfortable acceleration: $1 \div 3$ m/s²
- Comfortable deceleration: $- 5 \div - 2$ m/s²
- Minimum clearance (distance between two vehicles at standstill): $0 \div 3$ m
- Maximum deceleration: $- 8,8 \div - 2$ m/s²

It should be highlighted from the start how the study is focused on both ACC and CACC systems, in this Ex-Ante only the results concerning the ACC system (and thus related to the Highway Chauffeur system) are reported, please refer to [102] for the whole dissertation. As long as the impacts are concerned, the author found the high variance of results often bound to different ACC implementations, however some considerations were drawn. For example, on the basis of its bibliographical review the author stated that different car brands have differently tuned ACC (e.g. Tesla's ACC has a more sportive behaviour while the Volvo's one has a more comfortable driving style). Moreover, the possibility for the ACC system to be customizable to adapt to the preferences of the human driver is mentioned. An interesting subject that will be addressed often in the following paragraphs is that the users of an ACC system accomplish less lane changes, besides, mentioning "Towards an understanding of adaptive cruise control"², the following result is reported: ACC performances can lead to reductions in acceleration variances ranging from

² Marsden, G., McDonald, M., & Brackstone, M. (2001).

44 to 52%. Moreover, ACC systems were found to perform smoother braking actions when compared to the human driving in dense traffic flows, while more abrupt braking actions can arise in free flow conditions, due to cut-ins from other vehicles. An interesting conclusion that is recalled also in the simulations' design is that different types of jam can arise and the different causes can lead to different impacts of ACC systems.

The simulations carried out in [102] consider three different ACC systems, the traditional ACC, new ACC able to detect also vehicles on the other lanes and an improved ACC with reduced time gaps and reaction times. Only the latter two will be analysed in this Ex-Ante, under the hypothesis that an HC vehicle is at least able to detect vehicles on the other lanes, to predict their behaviour and to maintain reduced headways between itself and the preceding vehicle (while also responding readily to cut-ins). The car-following model employed is the Gipps model, tuned to adapt the behaviour to the one of the considered ACC systems. It should be noted, how the author often highlights in its work, that in the Gipps model the maximum speed that a vehicle can reach is restricted by both its own characteristics and the presence of the preceding vehicle. This constraint is defined by an V_b parameter. Another hypothesis imposed by the model is that the reaction time of an ACC-equipped vehicle is the same both for the longitudinal and lateral control, which means that an increased number of lane changes is obtained for higher efficiency of the ACC system. This is not necessarily true, as will be examined in the following paragraphs, an HC vehicle can perform more or less lane changing and overtaking maneuvers, indeed, depending on the aggressiveness of the control algorithm. The results obtained in [102], then, should be read with an aggressive behaviour of the HC vehicle in mind, rather than the opposite. Another important aspect that should be considered is that, in the simulations presented in [102], the ACC-equipped vehicle is considered able to keep the ACC engaged at full speed range (which means also for low speed values, in order to face congestion). This hypothesis allows to project more easily the impacts found by the author to an HC vehicle, as the one hypothesized in this Ex-Ante evaluation (even though no Traffic Jam Chauffeur function is mentioned). To simulate the different causes of congestion, the A15 highway in the Rotterdam area was chosen (the presence of the Port of Rotterdam, together with three junctions, guarantees high levels of congestion).

It should also be noted that an in depth calibration process has been carried out, on the basis of the typical traffic patterns from Google and of the traffic flows recorded by the National Data Warehouse. Please refer to [102] for the complete dissertation about this subject. While defining the behaviour of the different ACC systems considered in its work, the author adopted the

hypothesis (validated from literature) that the drivers of these vehicles are more aware of the speed limits and, therefore, the mean speed acceptance has a lower deviation (0,05) compared to the one of traditional car drivers. For an HC vehicle, this deviation could be set to 0, reflecting a perfect compliance to the speed limit.

As already mentioned, the study covers a broader range of scenarios but, to report only results relevant to the HC implementation, in this Ex-Ante only the newer ACC and the improved ACC systems will be analysed. A reduced reaction time accounts both for improved capabilities of the system, with lower sensors' delays, and for the ability to detect incoming cut-ins and react accordingly, avoiding abrupt braking actions. Another relevant parameter that should be highlighted, to support future modeling works, is the simulation step, equal to 0,2 s.

The indicators assumed for the carried out experiments are:

- Delay, density, speed and total number of lane changes at the experiment level
- Space time diagrams derived from detectors sets placed at 50 meters distance from each other
- Lane speeds, densities, flows and lane changes at section levels

Thus, simulations were run and the following results were obtained. First, the average impact at a network level of the newer ACC are:

- Slightly lower speeds
- The congestion arises and dissolves earlier and no impacts of market penetration levels are recorded
- Both increasing and decreasing delay times, the former result concerns mostly non congested scenarios while the latter results occurs due to relieves of congestion at specific bottleneck locations.

For the improved ACC it results that:

- Speed decreases for increasing of market penetration for uncongested scenarios, this is due to an increased compliance with speed limits. In congested scenarios, the average speed grows as the market penetration increases. Even low percentages of improved ACC seem to solve some local bottlenecks.
- The share of vehicles equipped with the improved ACC increases density in uncongested scenarios while the trend is the opposite in congested scenarios.

- A delay times decrease for higher rates of improved ACC, except for scenarios near to free flow in which the major compliance towards speed limits has a negative impact. Nevertheless, improved ACC-equipped vehicles seem to be able to solve congestion

The author makes also consideration on space-time diagrams at bottleneck locations obtained by its simulations. First, a weaving section near a junction is analysed. There an increased headway value produces a decrease in speed at these sections and, possibly, increased braking actions. These flaws have been identified both for the newer and the improved ACC category, the author concludes that the negative impacts are due to the improved reaction times of the systems that lead to an increased number of abrupt braking aimed at responding to vehicles merging in front of the vehicle. For a weaving section in which the traffic demand is close to the capacity of the road branch both newer and improved ACC systems have a positive impact on the speed that slightly increases for an increased share of ACC systems. The positive effect is attributed to the lower reaction times and to the increased headways that allow other vehicles to merge. Another section analysed is an on-ramp area, there an increased share of newer ACC-equipped vehicles affects very little the congestion that arises, both lower reaction times and decreased headways are factors affecting positively the traffic situation. Similar considerations are made about the improved ACC, even though it should be noted that the congestion problem is less severe when compared to the newer ACC scenarios. When an on-ramp section with a downhill slope is analysed, it results that both newer and improved ACC systems decrease congestion for higher market penetration levels. This is due to a smoother braking action performed by the systems at the downhill slope and to its reduced impact on the traffic upstream. Moreover, reduced reaction times mean that the vehicle responds more efficiently to the abrupt braking of the other, traditionally driven, vehicles. While analysing a similar scenario but with a spillback towards the city centre of Rotterdam, the results suggest that the ACC can be an effective means to increase traffic flow stability in congested scenarios comparable to this one. As mentioned before, different congestion types seem to be affected differently by ACC systems. For example, in another scenario analysed by the author (bottleneck corresponding to a reduction from 4 to 3 lanes), no enhancement of traffic flow or capacity were obtained for increased levels of market penetration, both for newer and improved ACC systems. The last relevant result reported in this Ex-Ante concerns weaving sections and how their length influences the impact of the two ACC systems considered. In fact, both positive and negative effect can be obtained, the first are due to the increased headways and to lower reaction times

while the latter are due to the increased braking actions needed to maintain the desired headway value. The author, from the simulations, concluded that, at short weaving sections, the two ACC systems have negative impacts while the opposite occurs for weaving section of normal length, improvements are obtained for increased levels of market penetration.

[102] is certainly a work full of interesting results and, for the sake of the dissertation, not every one of them can be analysed in depth in this paragraph. It should be mentioned, though, that the results at section level obtained by the author indicate that, at road section at capacity conditions, the two considered ACC systems have a homogenizing effect for speed, density and flows between lanes.

J. Wei, J. M. Dolan And B. Litkouhi, 2013. Autonomous vehicle social behavior for highway entrance ramp management

In [28] an interesting set of scenarios is considered: autonomous vehicles cooperating with vehicles merging from entrance ramps on freeways. An algorithm is designed by the authors to allow the autonomous vehicle to perform social behaviour on the basis of a Prediction feature and a Cost function. One of the challenges, when facing the issue of interaction between an autonomous vehicle and a manually driven vehicle, is that no form of cooperation occurs (unless some kind of DSRC is considered). In fact, it is not possible, for the HC vehicle, to estimate the other driver's intentions on the basis of the non-verbal communication that arises when two human drivers evaluate each other's most likely response. On the basis of similar considerations, the authors tried to enhance the decision-making system with a form of cooperation based on the foreseen intentions of the human driver on the other vehicle. Therefore, the designed algorithm evaluates the surrounding vehicles' intention, generate candidate strategies and chooses the best one on the basis of both the Prediction feature (which predicts the future traffic scenarios) and Cost functions. The intentions of the surrounding vehicles are bound to a probability obtained by a knowledge-based model that exploits the autonomous vehicle's perception system composed by the equipped sensors.

In the entrance ramp scenario, the designed algorithm considers the merging vehicle at the start point of the ramp and computes the point where the interaction needs to be completed on the basis of the widths of both the lane and the merging vehicle (beyond this point the autonomous vehicle is set to go back to normal ACC driving). Moreover, [28] only takes into account the longitudinal control to face the incoming merging vehicle, without considering the possibility of a lane change, therefore this paper is analysed in this paragraph and not in 2.3. about motion planning. The only parameter that the automated system changes is its acceleration, in response

to the inputs provided by the on-board sensors, namely d_{merge} , v_{merge} and l_{merge} (respectively the longitudinal distance, the speed and the lateral position of the merging vehicle). On the basis of these parameters the algorithm determines the value of the intention state of the merging vehicle that could be both yield or not yield. The perception system measures also d , v and l for the surrounding vehicles.

The estimation of the merging vehicle's intention is accomplished on the basis of its kept acceleration: "a decelerating vehicle is more likely to intend to yield", the acceleration value is obtained from its speed on a time interval. Other factors taken into account by the algorithm are both the forward distance from the automated vehicle, in case of yielding, and the backward distance if the merging vehicle wants to cut-in ahead. 10,000 simulations were carried out by the authors on the basis of the analytical definition of this problem that has been reported qualitatively, please refer to [28] for a complete representation of the problem. For this Ex-Ante, the relevant contribution is the description of the possibility for the HC vehicle to adapt its behaviour to other vehicles in critical points of the infrastructure, capability that can be enhanced by the means of V2X communications. The simulations' results showed that the algorithm was able to capture the real intentions of the merging vehicles, with a precision that grows with the approaching of said vehicles to the merging point. Once the probabilities concerning the future state of the merging vehicle and the surrounding traffic have been defined, candidate strategies are generated by the algorithm. To limit the computational burden and time, a discretization process is applied on the basis of the total speed adjustment time and the acceleration amplitude for the first and the second half of said time. This way the total speed adjustment time is split in two equal constant-acceleration segments. For each strategy thus generated, the prediction engine predicts the future traffic scenarios and, when the probability bound to the merging vehicle's intention reaches a certain value, the control strategy of the autonomous vehicle is tuned accordingly. This assessment is performed early enough, when possible, so that the behaviour of the autonomous vehicle itself can force the merging vehicle to converge to the predicted decision. For each generated scenario, a cost function is computed and takes into account: the time needed to perform the planned driving task, the comfort of the driver, fuel consumption and safety (which includes the distance from the surrounding vehicles and the braking differences between the other vehicles and the automated one).

The results of the simulations were compared by the authors to the ones obtainable with two other algorithms: the ACC one and the geoACC that considers also the road geometry and some rules influencing the yielding decision. The algorithm designed by the authors showed lower

speed variations and almost optimal values of distance between the vehicles when the merging one cuts in.

“In summary, the iPCB algorithm performs in the most reasonable and social friendly way among the tested approaches by interacting with merging vehicles on entrance ramps. It increases the smoothness of the velocity adjustment and also keeps the distance between merging and autonomous vehicles in a safe range.”

2.3. Lateral control and motion planning

As discussed in the previous paragraph, to retain longitudinal control a rather small set of parameters and environmental outputs must be considered and the main decisions concern the acceleration/deceleration regime. Safety is retained by the means of a well-tuned control laws, safe gaps between the automated vehicle and the preceding one and the perception of spaces and speeds in the actual driving lane obtained thanks to on-board sensors. Moreover, as long as only longitudinal control is concerned, no particular maneuvers must be decided and carried out by the HC vehicles (with the possible exception of an external vehicle cutting in, in which case only an increased deceleration is involved). For lateral control, additional information must be gathered from other lanes and the HC vehicle must be able to evaluate the benefits resulting from, for example, a lane changing maneuver also considering the safety constraints and risks related to this maneuver. Besides, the HC vehicle must evaluate the most likely behaviour of the other road users, their future acceleration values and driving direction, in order to engage an evasive maneuver should the need arise. Obviously both an evasive maneuver and a lane change involve different levels of accelerations and speed, which fall in the longitudinal control field, but will be analysed in this more inclusive paragraph. This subdivision is carried out to separate essentially two different kind of impact on Traffic Efficiency, Safety and Environment:

- ACC related impact, due to a more efficient longitudinal control law and, potentially, to reduced headways (evaluation based on the works analysed in the previous paragraph). The hypothesis which involves an ACC system both efficient and comfortable is kept for all the rest of this Ex-Ante report but depends on the OEMs market strategies and products.
- Impacts related both to more or less efficient maneuvers (overtaking, lane changing, ramp interactions etc.) and to the motion planning process that determines the HC vehicle’s itinerary as long as a valid ODD is perceived.

In this paragraph, an (hopefully) understandable review of an autonomous vehicle's driving process is carried out to highlight the system functioning and how, finally, an HC vehicle is foreseen to behave on public roads. It is important to understand what a vehicle in an automated driving state can accomplish and what are the most likely implementation scenarios that can be derived on the basis of the solutions found in bibliography. Without this work of literature, in fact, it could prove to be difficult or impossible to assess the impact of a generic system without specifically addressing an OEMs product. To assess every impact, every possible function implementable within and Highway Chauffeur system must be analysed. It should be clear, though, that especially in the short term an L3 system won't be capable of every task described in this Ex-Ante and that first field tests will most likely assess the most basic functions/operational tasks accomplishable by a Highway Chauffeur system.

Thus, in this Ex-Ante a general approach is preferred and, therefore, the Highway Chauffeur considered in its jointed implementation with Day C-ITS services is a general system whose capabilities and limits are defined on the basis of what is found in literature. Besides, as a general approach, most of the impacts of a cooperative services broadcasted on an HC vehicle are going to explore if the ODD of the automated system can be incremented and how the HC vehicle's Object and Event Detection and Response (OEDR) faces the driving scenarios.

It is therefore beneficial to describe ODD and OEDR capabilities as done, for example, *in [60]*. As mentioned in [60], tests should also evaluate how the system can return to a minimal risk condition and, in the evaluation methodology proposed in this Ex-Ante, how a C-ITS can ease the fall back condition or the take-over transition will be analysed.

This guidance work defines the OEDR as "the detection (...) of any circumstance that is relevant to the immediate driving task". Thus, until a HC vehicle remains in its ODD, it should be able to detect and respond to the surrounding road users while retaining an acceptable level of safety. Another relevant concept addressed by the document is the Behavioural competency which represent the ability of the automated vehicle to regularly travel through traffic, staying in the intended lane, obeying traffic laws and responding to the environmental changes accordingly. Referring to the Californian program PATH, [60] lists an example of behavioural competencies, some of which are listed below (the ones judged more relevant to the assessment of the impacts deriving from a jointed implementation Highway Chauffeur system – Day 1 C-ITS):

- Detect and Respond to Speed Limit Changes and Speed Advisories
- Perform merging maneuvers
- Performing overtaking where permitted
- Perform Car Following (Including Stop and Go)

- Detect and Respond to Lane Changes
- Detect and Respond to Static Obstacles in the Path of the Vehicle
- Detect and Respond to Work Zones and People Directing Traffic in Unplanned or Planned Events

Besides, from a safety point of view, an automated system should be able to identify pre-crash scenarios and face them, especially when dependant from the automated vehicle itself.

In [60], many indications are provided about the safety assessment prior of the deployment of the automated system and won't be reported here.

Another relevant NHTSA document, [39], lists the maneuver that a vehicle driving in automated mode should be able to operate, also mentioning road work areas and pointing how adverse weather conditions can be cause of exit from the system ODD (the passage of control from the automation to the driver can be critical, given the instantaneous nature of some of those events). Still in [39], more than 20 reports or journal articles were reviewed and the key attributes of pre-crash scenarios were identified, ranging from the merging and road departure maneuvering to the effects of fatigues and distraction. For a more comprehensive list please refer to [39].

Pendleton, D.S., Andersen, H., Du, X., Shen, X., Meghjani, M., Eng, H.Y., Rus, D. And Ang, H.M., 2017. Perception, Planning, Control, and Coordination for Autonomous Vehicles.

In [46] an overview of the autonomous vehicle software systems is presented.

“The core competencies of an autonomous vehicle software system can be broadly categorized into three categories, namely perception, planning, and control [...]. Also, Vehicle-to-Vehicle (V2V) communications can be leveraged to achieve further improvements in areas of perception and/or planning through vehicle cooperation.”

As explained in [46], Perception lets the system collect information about the environment and its own position, Planning lets the system bring the vehicle from a starting point to the destination avoiding obstacles while optimizing the process and Control let the lower controllers execute the actions (such as steering, braking and accelerating) planned by the higher controllers.

As long as the environmental perception is concerned, the tools needed from an automated vehicle are the sensors implemented on-board and, possibly, V2X communications able to provide information out of the sensors' range. The two tasks that must be carried out to make

possible the automated driving (and therefore the Highway Chauffeur system) are: road surface extraction and on-road object detection. From the former one an important information that must be extracted concerns the Lane Line Marking and the system must be capable of estimating the vehicle's position with respect to the detected lines. The task can prove to be difficult in situations where the lighting conditions are suboptimal, when shadows from external objects falls on the markings or the paint is worn-out.

Most of the algorithms employed must accomplish both a lane line feature extraction (by edge and colour detection, for example, fitting the pixels into different models to estimate the marking's shape) and the estimation of the vehicle's position related to the markings resulting from the model. To carry out this last task it is not sufficient a 2D image, the depth must be estimated by the on-board sensors too (LIDARs, for example, can get 3D images while simple cameras cannot).

In [46] a complete description of the available sensors on the market, their functioning, capability and limits, is presented but is not going to be reported in this Ex-Ante.

Road surface detection is needed to assess where the autonomous vehicle can drive without collision and is carried out mainly following three kind of approaches: feature/cue based detection, feature/cue based learning and deep learning. Again, an in-depth explanation of the capabilities and limits of the three approaches is performed in [46] but is not going to be reported in this Ex-Ante (which is more focused on the impacts rather than the functioning of the system). An important function that each vehicle falling in the L3 automation level, generally, should be able to perform is data fusion. As stated in [46], each sensor can perform one task better than the others, especially when different weather and lighting conditions are involved, therefore a way to put together all the relevant information provided by each sensor is needed.

For example: "LIDAR is able to produce 3D measurements and is not affected by the illumination of the environment, but it offers little information on objects' appearances; conversely, camera is able to provide rich appearance data with much more details on the objects, but its performance is not consistent across different illumination conditions; furthermore, camera does not implicitly provide 3D information." It should be noted, though, that the fusion mechanisms are still being developed and are not in a definitive stage, thus there is room for improvement, especially when considering the possibilities granted by the development of deep learning algorithms.

A different kind of fusion concerns the Localization problem, solved using both satellite-based navigation systems and inertial navigation systems. The formers can guarantee an accuracy ranging from tens of meters to a few millimetres depending on the signal strength while the latter

are independent from external equipment or signal strength but the measure errors are divergent over time and must be limited by the means of both GPS measures and/or digital maps.

The Perception alone performed by the vehicle doesn't still allow to define its behaviour while driving on public roads. The Planning task is based also on the ability of the vehicle to perceive the environment and its own position and can be divided in mission planning, behavioural planning and motion planning as stated in [46]. Mission planning mostly concerns the route chosen by the vehicle starting its journey and updated on the basis of what is perceived by the system during the travel. The behavioural planning function guarantees that the automated vehicle follows all the mandatory road rules and interacts in a safe way with other road users (to do so, an important metric often employed in literature is TTC, Time to Collision). Motion planning is carried out to decide the actions needed to reach the planned goal, avoiding collisions, and must guarantee certain levels of computational efficiency and completeness (conflicting objectives). Many solutions and algorithms have been proposed in literature to avoid computational demanding searches for all the possible paths while scanning for all the possible spaces occupied by obstacles. Important approaches to face this kind of challenges have been reported in [46]. Once the Planning process is carried out, the Control task makes the low level controllers accomplish the desired longitudinal and lateral control. The authors state that the most common controller structure is the Feedback one which makes sure that any deviation from the planned behaviour is corrected. The PID controller, for example, performs Feedback control and is often cited in literature, its control law is based on the error signal but, for this reason, it only responds to errors as they occur and doesn't prevent them. Another limitation of this kind of controller is that only one mechanism computes the response to noises and modelling errors. Adding a feedforward term in the controller can remove errors and disturbances before they happen, as stated in this work, but is more difficult to model. Nevertheless, the feedforward term can generate a reference trajectory verified and corrected by the feedback controller. A solution able to face the autonomous system's nonlinearities is the Model Predictive Control which performs a prediction on a short time horizon and computes the optimal solution. On the basis of their bibliographical review, the authors stated that MPC controllers have already been applied for longitudinal control, lane keeping functions, braking, steering and trajectory tracking problems and are based on a cost function that must be optimized to obtain the optimal input sequence for each control cycle.

Thus, the Control function of the software is used to find a control input which corresponds to the desired trajectory, the adopted approaches can be two: sensor based and dynamic based. The former is focused on the integration of the perceived environment without considering too

much the vehicle dynamics, the latter allows for enhanced comfort, safety and efficiency instead. The authors, then, carried out an overview of the available path and trajectory tracking methods that were divided in geometric methods and model based methods. The latter category, in turn, can be divided in kinematic models (which can perform better at low speed) and dynamics models (which perform better for higher speeds). Geometric Path tracking employs algorithms based on geometric relations, instead, and is able to derive the steering control laws for the vehicle.

This summary reported in [46] is aimed to describe how the vehicle performs the autonomous driving, please refer to the work for a more complete dissertation. The last important mention about this work concerns the possibility granted by Cooperative Systems and Communications, explicitly mentioned by the authors. For example, by the means of V2V and V2I communications, cooperative localization can be achieved: map merging can be employed to enhance the perception of single vehicles by aligning multiple local sensing maps or by localizing these maps on a global one to limit the communication resources requested by the task. Another information that can be broadcasted concerns the shape of vehicles and their relative orientation, details can't be derived by the autonomous vehicle's sensors alone. Besides, letting the automated vehicles communicate can enhance motion coordination, sharing future trajectories and identifying in advance potential conflicts in dedicated point of the infrastructure, possibly with V2I support. Obviously, higher is the risk associated with the cooperative task, the stricter must be the requirements fulfilled by the exploited V2X communication (requirements that should guarantee functional safety also for a system of systems or cooperative systems, as defined for example in [111, 112, 113]). Namely, if the V2X communication influences the behaviour of the automated system without the supervision of the human driver, both safety and liability issues could arise.

Best, A., Narang, S., Pasqualin, L., Barber, D. And Manocha, D., 2017. AutonoVi: Autonomous Vehicle Planning with Dynamic Maneuvers and Traffic Constraints.

As far as algorithms are concerned, in [7] a case is presented in which the autonomous vehicle supports dynamic maneuvers without breaking the constraints and traffic rules. Lane changing, swerving and braking are all implemented as possible maneuvers and, to carry out each maneuver, the vehicle must take into account its own dynamics, the surrounding traffic, its behaviour and the sensors' environmental perception. One of the main contribution of this article is the presentation of an algorithm that doesn't hinder lane changing or overtaking maneuvers

and is less conservative than the average control algorithm. Actually, in the article four different algorithms are presented by the authors: Optimization-based Maneuvering, Data driven Vehicle Dynamics, Collision avoidance with kinematic and dynamic constraints and Trajectory Planning with Traffic Rules and Behaviors.

The capability of the system in avoiding a collision was evaluated considering also vulnerable road users like pedestrians. From the bibliographical review carried out by the authors some considerations can be derived:

- As long as vehicle kinematics and dynamics modeling is concerned, the trade-off is mostly between the required computational power and the evaluation of more precise vehicle dynamics
- Approaches to path planning are based, in general, on occupancy grids, random-exploration, driving corridors and potential-field methods. Also, game-theoretic approaches can be employed to foresee the driver behaviour

Besides, the algorithm developed by the authors uses an optimization approach to determine when a lane change maneuver is appropriate and encourages it as long as safety is guaranteed, changing the inputs of steering and acceleration. The algorithm firstly searches for a route, given the road network, then a trajectory is drawn according to the lane markings and the surrounding traffic flow, on the basis of which control inputs are generated and evaluated for dynamic feasibility and, if deemed feasible, an optimization-based choice is performed. It should be noted that when dynamic feasibility is evaluated, controls that could lead to dangerous scenarios like skidding are excluded.

The kinematic model is employed to generate the trajectories, instead. The functions used to control the vehicle's driving are the throttle and the steering by the means of which the vehicle's motion was described by the authors as follows:

$$\begin{aligned}\dot{p}_x &= v \cos \theta \\ \dot{p}_y &= v \sin \theta \\ \dot{v} &= A(v, u_t) \\ \dot{\varphi} &= \Phi(\varphi, u_s) \\ \dot{\theta} &= \frac{\tan(\varphi)}{(L_F + L_R)} v\end{aligned}$$

Where A and Φ are the acceleration and steering functions, p is the position of the centre of mass, v the speed and θ describes the vehicle's heading and orientation. L_f and L_r represent the distance between p and respectively the front and rear axles. It is important to highlight how the

vehicle's state is updated at fixed time intervals, on the basis of which the values of acceleration and steering are changed, if needed. The kinematic model alone is not able, though, to guarantee automated driving. The authors assumed, in fact, the presence of a sensing module able to locate nearby vehicles, vulnerable road users and other obstacles, also providing their shape, speed and position. Moreover, in this work a PID controller is considered to transmit the set of feasible controls chosen by the model to determine the final speed and steering angle of the vehicle.

Thus, the algorithm is designed in four operational stages:

- A route is defined using a GIS database, to reach the chosen location a road-transition maneuver is planned considering as vehicle's behaviour merging, turning and driving straight
- A guiding path on the current lane is defined based on a set of waypoints, each one of which is connected by a circular arc that sets the initial target speed and steering. The stretch so defined can be abandoned in collision avoidance maneuvers.
- On the basis of the guiding path a set of feasible control inputs are computed.
- An optimization process selects the best maneuver and the resulting control values.

To implement the collision avoidance function, the authors considered the theory of Control Obstacle. For each potentially colliding object, all control inputs that could lead to collision in a given time horizon are included in the *control obstacle*. In their approach the authors assumed no possibility to observe the behaviour of the other vehicles in the limited time horizon, which means that the autonomous vehicle must avoid collision independently from the actions of the other vehicles. Considering all the control obstacles defined for each potentially colliding object as boundaries, the remaining sets of controls are collision-free and can be employed. Actually, the computational burden that must be faced to define every control obstacle and the resulting boundaries is rather high, for this reason the authors used a sampling strategy based on the steering and acceleration values. The sampling process is designed for the solutions to deviate the least possible from the predefined route, facilitating within-lane avoidance maneuvers.

The optimization process carried out to evaluate the upcoming maneuvers is based on a cost function that considers the following contributes:

- A path cost that considers the speed, the distance from the centre line of the lane and the vehicle's desire to progress along its current path
- Comfort costs considering both the acceleration and deceleration values and the sharpness of the turnings

- Costs associated with the lane changing maneuver
- Costs associated to the proximity of the surrounding neighbour objects, the kind of the neighbour defines the acceptable proximity value.

The authors then reported the experimental results in [7], different scenarios were considered relevant and therefore simulated. The autonomous vehicle proved to be able to pass a bicycle, to stop in order to avoid a pedestrian and to perform an emergency stop at highway speeds, responding to a preceding vehicle's sudden stop (which is particularly relevant for the Highway Chauffeur System). The vehicle seemed also able to switch between lanes while approaching a turn in the most efficient way and to respond to another car suddenly entering its lane ahead of it.

Katrakazas, C., Quddus, M., Chen, W. And Deka, L., 2015. Real-time motion planning methods for autonomous on-road driving: State-of-the-art and future research directions.

In [31] the authors carried out a review of motion planning methods for automated vehicles. It should be highlighted that an HC vehicle can be considered automated as long as it operates in its ODD, that should always be kept in mind when referring to this bibliographical review. As stated in this work, the automated driving consists mostly of finding a path, searching for the safest maneuver and determining the most feasible trajectory. Again, it should be highlighted that the authors mentioned explicitly V2X communication as improving factors to the automated driving. The paper focuses on path, maneuver and trajectory planning, though, which are based on vehicular dynamics, obstacles, road geometry and interaction with the surrounding traffic. To define the planning procedure, the authors identified the state of the vehicle as function of the position, its orientation, its linear and angular velocities. The vehicle can transition between different states thanks to actions (an action is a system input in terms of, for example, acceleration and/or steering angle). A path is defined as a “(...) geometric trace that the vehicle should follow to reach its destination without colliding with obstacles”. Besides, the vehicle must follow traffic rules and stay within the roads geometrical constrains and lane boundaries. The planning cycle described in this paper is composed by the generation of several trajectories on the basis of cost functions, the trajectory is updated at regular intervals depending on the frequency to which the sensors data are updated (for example, during the VisLab challenge this rate was set equal to 100 ms, as stated in this paper and in [9]).

The path definition can be accomplished by making the physical space surrounding the vehicle a state space which is the set of all the possible states (as defined above) in which a vehicle can find itself. Besides, thanks to the sensors' information gathering a digital map can be drawn, on which the planning can be performed. To face the computational burden that this task requires, then, the authors reported the most acknowledged methods and techniques used to decompose the space: Voronoi diagrams, occupancy grids cost maps, state lattices, driving corridors.

Planning "(...) concentrates on finding the best path for the vehicle to follow while taking into account the constraints of the vehicle's motion model, waypoints that the vehicle should follow and the traffic environment, including static and dynamic obstacles". The path search is also indicated by the authors as the input for the choice of the best following maneuver, the engaged maneuvers can, in turn, change the path planned establishing a feedback loop. The planning modules are: Route planning, search space for planning, path search and manoeuvre search (iteration), final path and trajectory planning.

It is also important to note how the waypoints obtained from the route planner can be updated on the basis of external information, received for example by a C-ITS service like Roadworks Warning as will be analysed in the following paragraphs.

The search for the best path is an iterative process carried out by the algorithms that employs the results from the previous search to increase the computational speed. This can lead to two approaches that are examined in this study: Rapidly-exploring Random Trees and Lattice Planners. They won't be analysed further in this Ex-Ante, please refer to [31] for the complete dissertation.

For this Ex-Ante Evaluation, what is stated about the maneuver planning process can be relevant, instead. According to the authors, to plan a maneuver both the behaviour of the automated vehicles and of the surrounding road users must be taken into account and anticipated somehow. On the basis of the dynamically feasible paths obtained, the maneuver planning module chooses the safe and most efficient one after checking the possible interactions with the surrounding road users. Two possible approach are identified by the authors:

- Motion modeling and obstacles prediction
- Planning with emphasis on obstacle prediction and decision making

In the bibliographical review carried out by the authors, the tools employed to estimate the Risk can be risk indicators or probabilistic gap acceptance models. In these cases, more precise results can be obtained but computational burden becomes an issue while predicting the motion

of the surrounding obstacles. Risk estimation can also be accomplished by the means of decision theoretic approaches that assess the situation and formulate a decision theoretic problem in order to decide the following maneuver (the authors state that this kind of approach is well suited for highway maneuvers and, therefore, can be exploited by the Highway Chauffeur System). However, it is highlighted by the authors how these approaches don't exclude each other and can be, therefore, combined. Once defined the path and the best maneuvers a trajectory can be generated optimizing a cost function that accounts both for dynamic constraints, comfort and safety.

In the last chapter of their work, the authors listed the limitations that an automated system must face. The first one concerns the obstacle handling and the prediction of the surrounding road users' behaviour, which is performed without considering the interactions between all the road users. The inability of the on-board sensors to detect the situations around corners can impose overly conservative approaches or involve safety-critical scenarios, it should be noted, though, that for the HC vehicle this kind of issues shouldn't be prohibitive because its ODD is confined on highway roads. Additional barriers that could prove to be challenging, instead, are the ones involving the real mechanical capabilities of the vehicle, able to influence its maneuvers, and how they change with weather conditions (a wet road surface must be taken into account while calibrating the braking). This issue can be tackled by C-ITS services like Hazardous Location Notifications, as will be explained in the following paragraphs.

Besides, the authors explicitly mention the need for data collected during field tests that can help to calibrate the control algorithms and the interaction with the surrounding traffic. During the activities that C-Roads Italy is going to perform, a step in the right direction is going to be made thanks to the implementation of a Highway Chauffeur vehicle that will drive on public roads receiving some of the Day 1 C-ITS services' messages.

These activities should tackle another need mentioned in [29] where is stated that Field Operational Tests are fundamental to demonstrate safety, security and reliability of L3 systems and that the dissemination of best practices for the implementation of automated driving is beneficial to promote the assessment of societal, economic and ecological benefits.

Suh, J., Kim, B. And Yi, K., 2016. Design and Evaluation of a Driving Mode Decision Algorithm for Automated Driving Vehicle on a Motorway.

In [58] an algorithm to manage lane changing maneuvers is presented, the design is based on the capability of the automated vehicle to switching between two driving modes (lane keeping and lane change) on the basis of a cost function. The authors chose to employ a model

predictive control (MPC), already mentioned in [46], with constraints to transmit the longitudinal and lateral control to the vehicle. The MPC makes the algorithm able to minimize the cost function considered without breaking any constraints, thanks to the prediction of the future states of the neighbor obstacles. This prediction guarantees safety while determining the desired acceleration and steering angle, drawing a safety driving envelope around the automated vehicle that takes into account the desired driving mode and the behavior of the surrounding road users. The future state of the automated vehicle is predicted too, by the means of the lower level controller's inputs and of the information received by the equipped sensors. The algorithm designed by the authors determines the desired driving mode taking into account the status of both the actual lane and the adjacent ones. Besides, the approach assumed in the paper doesn't assume that the surrounding vehicles keep their current behavior during the time interval considered for the estimation but predicts their behavior based on probabilistic prediction. The first evaluation is carried out about the constraints such as road geometry and traffic rules (the assumption is that no vehicle breaks mandatory prescriptions), moreover, after a lane changing maneuver, the vehicle that performed it is assumed to keep its new lane for a certain time interval. These assumptions made from the authors don't affect the effectiveness of the approach.

The approach held by the authors in this paper aims to predict the future state of surrounding vehicles by the means of a path-following model able to generate their future desired yaw rate and to predict their future states. On the basis of this estimation, the algorithm designed in [58] can determine the desired driving mode ensuring safety. The cost function compares the two driving modes and let the lane changing maneuver start if its more convenient for the automated vehicle, this advantage is based on the acceleration value needed, the minimum distance from the surrounding vehicles and the difference between the desired speed and the adopted one. The lane change direction is decided considering the status of the adjacent lanes, moreover the algorithm is also able to estimate the lane change risk on the basis of TTC (Time-To-Collision). If, during a lane changing maneuver, there are adjacent vehicles, the safe driving envelope makes the vehicle keep safe distances considering not only its own envelope but also the ones of the surrounding vehicle (which generate an environmental envelope).

An environmental envelope is defined during the lane keeping mode too, especially when adjacent vehicles exist, this way the automate vehicle can retain safety also when external vehicles cut-in before it. It is important to note that the authors assumed a sampling time horizon equal to 0.1 s and a prediction horizon equal to 15 samples. Once defined this framework the

authors defined the longitudinal MPC problem to determine the steering angle and the longitudinal acceleration needed to retain safety.

HAO SUN, WEIWEN DENG, SUMIN ZHANG, SHANSHAN WANG And YUTAN ZHANG, 2014. Trajectory planning for vehicle autonomous driving with uncertainties

In [24] the uncertainties of the driving environment are considered and dynamic trajectory planning is defined to allow automated vehicles to drive retaining safety. The trajectory planning process defined by the authors makes the automated vehicle achieve a safe, comfortable and efficient lane changing maneuver considering the overall collision probability of each one of the candidate trajectories. The authors described three approaches in modeling the evolution of dynamic obstacles:

- Worst case approaches (the obstacle is targeting the automated vehicle)
- Dynamic based approaches (the future state of the obstacle is assumed based on its current state)
- Pattern-based approaches (typical moving patterns are considered, each one with certain statistical characteristics)

All these approaches try to predict the trajectory of surrounding vehicles, the authors in this paper defined a method to plan the automated vehicle's trajectory while taking into account the surrounding uncertainties, instead. A traffic vehicle model taking as inputs random variables and certain probability distributions is employed to obtain an overall collision probability and evaluate lane changing maneuvers. To design the mentioned traffic vehicle model, the authors considered the movement of surrounding vehicles governed by:

$$\dot{x} = f[x(t), u(t)]$$

Where x is a state variable such as speed and u an input variable such as steering, braking or throttle inputs. The future state of the vehicle can be determined by its initial state $x(0)$ and by the input $u(t)$ received during a certain time interval. Because the initial state can be perceived by the autonomous vehicle's sensors, the uncertainties are mainly bound to $u(t)$, the authors in fact acknowledge the uncertainties in sensor's measurements but in this paper focus on the unpredictability of the surrounding traffic. To evaluate the future state of a neighbor vehicle in the short time, the authors assumed its speed remaining constant and the only relevant input being the front wheel angle (the probability distribution characteristic of its position is a non-

linear transformation of the front wheel angle). A Gaussian distribution is assumed and a non-linear transformation to the xy coordinate domain is performed to evaluate the future state of a neighbor vehicle.

For the algorithm to plan the trajectory of the automated vehicle, all its possible trajectories are computed by a vehicle-model-based trajectory generator and, for each one of them, a collision probability is estimated on the basis of the future state of the surrounding vehicles and the related uncertainties. A maximum acceptable collision probability is defined, below which each trajectory is considered safe and is compared with the others to choose the optimal one also taking into account efficiency and comfort. For each safe trajectory, in fact, the resulting vehicle's position, orientation and speed can be calculated with sufficient precision and used to evaluate efficiency and comfort (which can be weighted to favor one or the other). Knowing what is the desired trajectory, in fact, it is possible to estimate in advance the future lateral acceleration and the lateral position. Finally, this approach was used by the authors to evaluate a lane change model in which the vehicle drives in a way that the maneuver consists of two symmetrical circular arcs with the same radius. The lane changing maneuver was carried out by the automated vehicle in simulations on the basis of the defined algorithm. The simulations conducted by the authors to test the proposed algorithm showed that no collision occurred during the maneuver, also the efficiencies obtained for different weights were compared.

Schmeitz, J. Zegers, J. Ploeg And M. Alirezaei, 2017. Towards a generic lateral control concept for cooperative automated driving theoretical and experimental evaluation

In [1] a lateral controller aimed at accomplishing lateral vehicle control is designed, mainly focused on lane keeping and vehicle following driving modes. Besides, in this paper different inputs can lead to different lateral control strategies, based, for example, on single point information rather than path information. The former situation can happen when the automated vehicle follows a preceding one too close and the lane marking are not detected/well defined on the road, if that's the case the vehicle can keep the small headway fusing camera and radar measures to stay aligned to the preceding vehicle. Feedback control can be achieved in the same fashion and be derived both combining lateral displacement and heading error or based on a lateral displacement evaluated at a look-ahead distance from the preceding vehicle. Designing the lateral controller object of this paper, two major assumptions were made: highway driving and complacency to the traffic rule by every road user.

The lateral controller is a single-track model in which the objectives are to make the center of gravity of the vehicle follow the planned path and to orient its longitudinal axis accordingly. These

two objectives are evaluated on the basis of the lateral position error and the yaw error, respectively, besides the yaw rate is employed together with the lateral velocity to represent the vehicle dynamics. The system so defined varies linearly with the parameters (specifically with the longitudinal speed value) and needs a feedforward term to avoid lateral position errors while driving tight curves in the highway scenario. The analytical presentation of the lateral controller reported by the authors is left to [1], please refer to the paper for a complete exposition. The paper then compares the two possible feedback control mentioned above: path information and single point information, also the possibility to switch between the two feedback control as the need arises is considered. The controller based on path information can rely on more than one measurement, which can't be said about the single point information. However, the path information, to function properly, needs the road curvature and the lane marking while the single point approach doesn't and relies on a single measurement. Besides, the path based controller can regulate the error to zero, unlike the single point one which can suffer from errors arising from curvature transients. In order to correct the errors, the modelled front wheel steered vehicle can only move laterally following a circular path and, thus, the controller tries to reduce the lateral error (before a certain look-ahead distance) by calculating the right radius and imposing it to the low-level controller.

The generic lateral controller introduced by the authors can switch between both path based and single point based strategies, simulations were carried out to assess its performances. A tight highway corner (radius equal to 750 m) was driven by a vehicle at 120 km/h, the main difference between the two control logics was the measured lateral error, the single point preview controller cuts the corner at the start of the road segment and steers back too early, moving outwards. After the simulations, on-road tests were conducted and resulted in tracking errors of similar magnitude in both controllers.

September, 2011. HAVEit Highly automated vehicles for intelligent transport The future of driving Deliverable D61.1 Final report.

In [47] a paragraph is dedicated to a specific scenario that is going to be confronted in chapter 4: Automated Assistance in Roadworks and Congestion. This work is based on the results of the HAVEit project, within which a comfort focused application has been developed and called ARC. Both longitudinal and lateral control can be entrusted to the automation in roadworks scenarios in which the speed ranges between 0 and 80 km/h, the lateral control is achieved by the means of a Lane Keeping system (which is composed, also, by a virtual Wall algorithm that poses lateral boundaries and applies a torque on the steering wheel to direct the vehicle). The

virtual Wall algorithm can also be applied to make the automated vehicle able to face too narrow lanes (that often arise when roadworks apply changes on the road topology). For the details of both the HAVEit and the ARC architectures please refer to [47], here only the features judged useful to later assess the jointed impacts of the Highway Chauffeur system and of the Roadworks Warning C-ITS will be reported (for this reason only the highly automated scenario is considered). As long as longitudinal control is concerned, the ARC vehicle can tune its speed values according to the speed limits detected by the cameras on the signs on the road side. The lateral control is achieved, instead, mainly through the detection of the lane boundaries and the resulting implementation of the virtual Wall algorithm that applies a counter torque if the ARC vehicle gets too close to a boundary (vehicles driving besides are considered as wall too). It should be noted that experiments were carried out to assess the ability of the ARC system to keep the vehicle safe while driving through a roadworks but no entrance in the roadwork area was effectively performed with the highly automated system engaged (only the partially automated system was tested in this scenario, instead). Nevertheless, the highly automated mode of the ARC system proved to be able to pass through the road construction site avoiding collisions both with beacons and guard rails. The ARC system is described more in deep in [76].

“With this, the driver could feel some virtual Wall, on which he could even lean on.”

The virtual Wall algorithm designed for the ARC vehicle aims to confront the critical situations that a Lane Departure Warning system can't face. The maximum counter force applicable by the system to the steering wheel is equal to 4Nm and the actual value is adapted as a function of:

- Distance to barrier (that is identified through the perception system)
- Angle to barrier
- Curvature of barrier
- Steering angle

Moreover, the intervention zone is calculated considering these factors and serves as a trigger to apply the counter force and to take back the vehicle also while in the uncritical scenario. Some differences are considered when applying the counter torque, for example for lane markings this intervention is softer than 4Nm while to avoid surrounding vehicles the counter torque starts earlier.

Madigan R., Louw T., Merat N., 2018. The effect of varying levels of vehicle automation on drivers'lane changing behavior

[114] is a work particularly relevant while analyzing possible lane changing behaviors and the impact that different levels of automation can have on the drivers. In this work, developed within the activities of the AdaptIVe project, the lane changing behavior kept by the drivers during non-critical take-over situations has been analyzed and reported. Three scenarios were compared: manual driving, partially automated driving and conditionally automated driving that can be considered L3, even if the lane-changing maneuvers performed during the tests had to be triggered by the drivers (only triggered and not carried out, the system was able to perform such maneuvers by itself). In the last two scenarios, the ACC headway was set to 2 seconds. The “trigger approach” exploited in the L3 scenarios can be rather useful, especially during the field test phase in which some of the maneuvers should still be validated by the human driver, the same can be said about cooperative messages and about how V2X communication are still facing some issues related to functional safety and the resulting integration with the on-board software, as stated in the previous paragraphs.

The main aim of this research was to assess the “quality of driver-initiated take-overs in non-urgent scenarios”, including in the take-over maneuvers also the ones only triggered by the driver (once re-engaged in the driving loop) by the means of the indicators lever and carried out by the system. Through the virtual simulator of the University of Leeds, 29 participants completed a three lane motorway, through which 12 overtaking maneuvers were caused by a slower vehicle ahead and could be performed both to the left and to the right lane.

It should be noted that, even if in the conditional automation scenario the overtaking maneuvers were carried out by the system, the drivers were required to remain in the loop through all the overtaking (until the ego vehicle returned in the central lane).

The first output indicator was the response time (“from when the lead vehicle entered the driver’s lane to the time the indicator was first pressed”) that resulted higher for the partially automated driving. This seems reasonable and was explained, by the authors, as due to the time needed for the drivers to re-take situational awareness before shifting from the automated mode to the manual one. Still, the time needed to gain situational awareness was, on average, equal to one second and the time needed for the overtaking maneuver in the partially automated driving scenario never exceeded 30 seconds.

Another metric exploited by the authors was the inverse Time To Collision in order to provide an indicator for the visual looming effect (caused by the vehicle ahead appearing on the ego lane). The inverse Time To Collision didn’t vary between the three tested scenario but a relevant output

is the Time To Collision deemed as comfortable by the drivers as overtaking time (please note that this kind of result can vary at national but also at regional level). While analyzing the drivers' lateral positioning, the speed profile and the steering behavior assumed during the overtaking in the partially automated driving scenario, a worse performance of the partially automated driving was recorded when compared to the manual driving.

“Our results show that when asked to respond to elements in the environment i.e. a slow moving lead vehicle, drivers had slightly longer response times in PAD than in manual driving or CAD, and got closer to the lead vehicle before initiating a lane-change. This provides some support for the idea that drivers will take additional time, when available, to regain an understanding of the situation before re-entering the vehicle control loop”.

Moreover, 60% of the drivers preferred the conditionally automated system to the partially automated one, which scored a percentage of 36,7%. This is another rather relevant result because highlights how not always the drivers prefer the system that mimics the most the human behavior (which is a rather popular statement in the literature about the topic).

“[...] given a choice, drivers prefer not to have to intervene with the automated system, even when not engaging in other tasks. In addition, the requirement for automated systems to mirror an individual's driving style may be less important than previously suggested [...]”

2.4. Take-Over time, HMI and Safety

Until full automation is reached and the driver is completely excluded by the driving loop, null (or almost-null) risk can't be achieved. Full automation alone is not even enough, even with the hypothesis that full automation is infallible (which is far from true) the surrounding road users surely aren't, therefore a 100% market penetration level must become reality too. Thus, the goal of zero casualties on public road is still far away, at least from the automation potentials point of view. In the short and medium term, it is also possible that an increased number of crashes will occur, caused by the limited ODD and the need for the automated vehicle to rely on the human driver to face unexpected system failures or scenarios. Transferring the control from the automation to the human driver isn't an easy task and involves a new kinds of risk, bound to the relationship of trust between the human driver and the system and to the time needed for the human to re-enter the driving loop and reacquire sufficient situational awareness to keep driving without consequences. This is the situation for an HC vehicle that can entrust the automation

with the driving task as long as the ODD conditions are fulfilled but must shift the control to the human driver as soon as the environmental condition changes or the automation suffers from a failure. As mentioned before addressing [39], for example, an instantaneous adverse driving condition can hinder the environmental perception capacities of the vehicle which must give back the control to the human driver. The human driver can be engaged in other activities, though, such as reading a book or watching a film (hypothesizing that the legal framework keeps up with the progress of automation) and can both decide to ignore the warning if provided in the wrong way or can need tens of seconds to evaluate the surrounding, the vehicle state and the emergency. This time can be excessive and safety can be compromised, some values are given in [39]:

- Short engaging timing equal to less than 3 seconds
- Medium engaging timing equal to 3 ÷ 10 seconds
- Long engaging timing equal to 10 ÷ 30 seconds

Besides, other challenges can arise if the driver results incapacitated, in [47], for example, the automated system is designed to switch into a minimum risk state if the driver doesn't react to the warning (the lateral control stays active until the vehicle is stopped). Therefore, in this paragraph, the transition of commands and the interactions between the driver and the system during take-over events will be analyzed, examining the most relevant works in the field. Again this operation is carried out not to obtain a bibliographical review (that still has been developed) but to derive the most likely implementation scenarios and functioning logics that will be the basis to assess the impacts of the jointed implementation of a Highway Chauffeur system and of Day 1 C-ITS. An important subject to highlight is how cooperative systems can potentially provide a huge amount of information to the system or to the driver. If, how and when they are presented by the means of a well-designed HMI (Human Machine Interface) is fundamental to avoid situations in which so many warnings are provided to the driver that she or he doesn't know to which one react or decides to completely ignore the alerts. This initial work of evaluation is carried out with the objective to enhance the safety obtained both by cooperative and automated systems in the short term, so that the promised benefits concerning safety, "(...) including, most notably, dramatic decreases in car crashes and automobile deaths" [14] could be achieved sooner and in a more efficient way.

It is also worth noticing that existing evaluation approaches can be applied together with the methodology derived in this Ex-Ante, a notable example is presented in [38]. This Safety Impact

Methodology, in fact, is designed to evaluate the safety impacts derived from cooperative mobility but considering metrics hardly obtainable from only field tests and/or in the short term (such as the Crash Prevention Ratio). Two relevant scenarios that can be evaluated with the SIM methodology are the ones involving rear-end collisions and lane change collisions.

The SIM approach is also mentioned in [52], where it is stated that it can be used to assess the safety impacts of V2V technologies, these evaluations consider a huge amount of real-world data, driver performance (such as type of reaction, reaction time and reaction level) and system performance. The outputs obtainable are: the reduction in conflicts, reduction in collision and reduction in impact speeds. In the same document it is also considered that automation may result in changes in trip making and in vehicle occupancy, therefore safety-evaluations on these time horizons must take into account these aspects and the related uncertainties.

In [20], another simulation tool is developed, designed to assess the safety-related impacts. In this deliverable drawn from the activities of the Adaptive project, a safety impact assessment methodology is proposed, aimed to quantify (finding measurable objective metrics) the impacts of automated driving on traffic safety. Besides, the evaluation work proposed aims to be balanced, which means able to consider also side-effects such as the risk of a collision with a following vehicle that arises when the longitudinal control law of the automated vehicle issues a braking action to avoid a collision with the preceding vehicle. Moreover, another consideration that should be highlighted presented in [20] is that during the assessment of the automated functions, a representative traffic environment should be designed (i.e. the traffic state, weather conditions, interactions with the other road users, etc.). The methodology defined in Adaptive, following the principles listed above, allows a virtual assessment based on simulations.

The methodology exploits both the results of the traffic scenario simulations and the analysis of accident data to identify the most safety critical scenarios for the automated function considered that are, then, investigated by the means of virtual simulations. It is relevant to highlight that the maneuvers included in the driving scenarios are:

- Approaching
- Lane change
- Close distance maneuver
- Starting and stopping
- Turning

While the scenario variables are:

- Light conditions
- Weather
- Road conditions
- Road type
- Infrastructure
- Road section
- Ego-Lane
- Macroscopic traffic state

The simulation tool defined uses three models to simulate the driver behavior, the vehicle model, the automated function and the driving scenario. The challenging scenarios identified in [20] by the means of the model and relevant for an HC vehicle are: the cut-in one (in which an external vehicle intrudes ahead the automated vehicle), end of lane (the lane on which the automated vehicle is driving comes to an end and a lane change must be performed), obstacle in the lane (again, a lane changing maneuver is needed) and approaching a traffic jam. Moreover, on the basis of the analysis of the accident data, the rear-end accident was considered too.

Another relevant consideration that should be done is that exiting the ODD of the Highway Chauffeur system doesn't inevitably involve that every automated function must return to the human driver as soon as the ODD is left. This possibility is referred as Degradation Cascade in [4], the degraded modes can function as fall-back solutions in which the safety level is reduced but still acceptable. An example is what could happen if the road markings are suddenly no longer recognizable or a camera failure prevents the vehicle from sensing them, in this scenario the HC vehicle could keep driving centered between neighbour vehicles while alerting the driver (in this reduced time interval the safety level is lower than before but still acceptable). Still referring to [4], if the driver doesn't take-over in 10 s, the system can bring itself to the less risky state that doesn't involve the driver (for example it can perform an emergency stop and activate the hazard flasher). In general, the least dangerous of the reachable states should be reached when the desired/safe state is not achievable. This approach is described also referring explicitly to the Highway Pilot function, the probability of an emergency stop should be equal to less than 10^{-6} . The hazard level of each alternative can be ranked simply following the ISO 26262 proceeding. Other notable values listed in [4] as an example are:

- The Highway Pilot in the example is considered active 10% of the driving time
- The average activation duration is about 30 min

- Statistically, on 1000 km, 5 points of interrupted lane markings can be encountered

Please note that the values listed above are just an example and shouldn't be taken as fixed, rather these metrics should be projected on each reality (at national, regional or local level) and in relation to the OEM's product. It should also be highlighted how a Highway Pilot system grants both automated longitudinal and lateral control but doesn't rely on the driver as fall-back solution.

In [37] some key research areas concerning the relationship between the human driver and the automation are highlighted, instead, such as mode confusion (relating to a certain aspect of the driver's situational awareness), the mode transitions and the controllability (whether false alarms, failures or system interventions are controllable by the driver), just to name a few.

Y. Li, Z. Li, H. Wang, W. Wang, L. Xing, 2017. Evaluating the safety impact of adaptive cruise control in traffic oscillations on freeways.

[95] is a work that faces a relevant issue concerning both the ACC and, especially, the Traffic Jam Chauffeur function. In fact, as stated in the previous paragraphs, an ACC system is just as safe and/or efficient as its parameters allow. Namely, how the HC vehicle respond to a braking preceding vehicle depends on the control parameters that the algorithm employs to assess the driving regime. On the basis of these considerations, the authors examined in [95] for what control parameters the ACC grants a safe driving regime in Stop-and-Go situations, especially when facing abrupt braking and potential rear-end collisions. Other relevant contributions of this paper are the evaluation of the effect on safety (in the Stop-and-Go and rear-end scenario) of a certain value of ACC-equipped vehicles among the traffic flow and the assessment of the potentialities of a fair share of ACC-equipped vehicles jointly with variable speed limits (a rather relevant subject, especially when compared to the C-ITS service In Vehicle Signage [70]). The focus of this paper is the analysis of rear-end scenarios that could arise with an ACC-equipped vehicle involved, therefore, the first consideration of the authors concerns the Automatic Emergence Braking which isn't considered in their simulations but should be accounted for when analyzing higher levels of automation. To evaluate how an ACC-equipped vehicle performs when facing a deceleration wave in congested flow, the first step made from the authors was defining when a rear-end collision is considered as occurred in the simulations. The condition is the following one:

$$d_a(n) + d_{de}(n) + d < d_a(n + 1) + d_{de}(n + 1)$$

Where $d_a(n)$ is the travelling distance of the leading vehicle n in the time t_a and $d_{de}(n)$ represents the same value but in the time t_{de} . d is, instead, the distance between the two vehicles at the time in which the following vehicle records the low speed of the preceding one. Being $d_a(n) + d_{de}(n) + d$ the location of the leading vehicle at the time $t + t_a + t_{de}$ (referred to a location x) and being the same consideration valid for the following vehicle (with the only difference being that the position of the leading vehicle is measured from the rear and the one of the following vehicle is measured from the front), the authors defined the following condition to identify rear-end collisions:

$$t_a + \frac{(v_2 - v_1)}{2b_m} - \frac{d}{(v_2 - v_1)} > 0$$

Where b_m is the maximum deceleration rate of the following vehicle.

Thus, an indicator R of the rear-end collision risk was defined (for the following vehicle):

$$R = t_a + \frac{\beta}{b_m} - \alpha d$$

With α and β as positive constants. The higher R , the more likely the rear-end collision. Moreover, the odds of having a rear-end collision in Stop-and-Go regime in this work are considered function of the perception-reaction time, the initial gap between vehicles and their deceleration ability.

Thus, by the means of a microscopic traffic simulator, the authors evaluated how different tunings of the IDM model, often employed in literature to simulate the ACC, could improve or worsen safety in a Stop-and-Go regime.

“Though the mechanism of commercial ACC system is very complex, the major differences between ACC and human driving is the intermediate process that can be captured by key parameters such as time delay, time gap, and acceleration rate. Thus, it is feasible to simulate the ACC system by modified human driving car-following models (...)”

The inputs for the ACC considered in the model are: the vehicle’s speed, the distance between itself and the preceding vehicle and their speed difference. The output obtained is the

acceleration/deceleration regime, moreover, relevant parameters contained in the model are: desired time gap, desired speed, time delay and acceleration-deceleration rate (which are all implemented in the IDM model).

To obtain the desired acceleration for a manually driven vehicle, the algorithm applies:

$$\dot{v}(t + t_a) = \max \left\{ b_m, \alpha_m \left[1 - \left(\frac{v}{v_0} \right)^\delta - \left(\frac{s^*}{s} \right)^2 \right] \right\}$$

$$s^* = s_0 + \max \left[0, vT + \frac{v\Delta v}{2\sqrt{(\alpha_m b)}} \right]$$

Where t_a is the perception-reaction time, v the speed of the following vehicle, s the gap distance between the two vehicles and T the safe time headway. The other parameters are listed in the table above. To simulate an ACC-equipped vehicle, the equations are rather similar but not the same:

$$\dot{v}(t + t'_a) = \max \left\{ b'_m, \alpha_m \left[1 - \left(\frac{v}{v_0} \right)^\delta - \left(\frac{s'}{s} \right)^2 \right] \right\}$$

$$s' = s_0 + vT' + \frac{v\Delta v}{2\sqrt{(\alpha_m b)}} = \text{modified desired time gap}$$

While implementing the variable speed limit, the only difference is in the value of $v(t)$ that can be limited if it exceeds the suggested one. Therefore, the model needs only eight parameters to be calibrated to define the ACC behavior: α_m , b , v_0 , s_0 , δ , T' , b'_m and t'_a . Relevant values that should be mentioned in this Ex-Ante are:

- The time gaps settable by the modeled ACC, equal to 0,6, 1,1 and 1,6 s
- The deceleration rates achievable by the ACC-equipped vehicles, equal to 2,8, 3,8 and 4,8 m/s²
- The time delay for the human driver, equal to 1,5 s
- The time delay in the ACC, equal to 0,5, 1 and 1,5 s (the 0,5 s value was chosen by the authors to account for the future technology development)

Thus, to evaluate which scenario is safety critical, the TTC metrics was employed by the authors and calculated as it follows:

$$TTC_i(k) = \frac{x_{i-1}(k) - x_i(k) - L_{i-1}}{v_i(k) - v_{i-1}(k)} \text{ if } v_i(k) > v_{i-1}(k)$$

$$TTC_i(k) = \infty \text{ if } v_i(k) < v_{i-1}(k)$$

The Time to Collision was, then, aggregated to represent different aspects of the safety-critical scenarios. The first derived metric is the Time Exposed Time to Collision (TET) which is the sum of the moments in which the TTC value is below a critical threshold (during all the simulation period for all the vehicles). The second derived metric is the Time Integrated Time-to-Collision (TIT) which indicates how much lower than the threshold the TTC values are (and, thus, revealing the severity of the safety-critical scenario). The threshold value chosen by the authors was equal to 1,5 and 2 s.

Exploiting this theoretical framework, the simulations were designed on a 10 km segment with 100 virtual loop detectors (one each km), the simulations lasted one hour and the first five minutes were the warm-up period. The traffic flow loaded on the segment was equal to 1600 veh/h/lane and a bottleneck was triggered between the detectors 9 and 10 after 10 minutes. The distribution of the ACC-equipped vehicles among the traffic flow was random. The first assessment was the one of the effects of different control parameters in the ACC algorithm on rear-end collisions. The baseline scenario was defined by $T = 1,6$ s, $t_a = 1,5$ s and $b_m = 2,8$ m/s² (human behavior). The vehicles tuned in this way showed a huge variation in their speed profiles once reached the slow traffic ahead. Other settings resulted in an unstable behavior, an exception being $T' = 1,6$ s, $t_a' = 0,5$ s and $b'_m = 2,8$ m/s², in this case the ACC showed a string stable behavior very quickly, preventing the Stop-and-Go traffic. Not only the performance of the ACC was evaluated through simulations, the safety effect was assessed too. With values of $b'_m = 2,8$ m/s², $T' = 0,6$ s and $t_a' = 0,5$ s the TIT decreased by 56.09% compared to the baseline scenario. With $T' = 1,1$ and 1,6 seconds the TIT decreased by 73,51% and by 100%, respectively while the TET decreased by 27,4% and 100% (always compared to the baseline scenario).

Thus, from the simulations, the authors concluded that a proper tuning of the ACC system could improve safety in Stop-and-Go scenarios. It should also be noted that, as mentioned often in [95], currently the ACC alone doesn't perform well enough in congested traffic but, in this Ex-Ante, a fine tuning of the algorithm is hypothesized to allow the HC vehicle to face congestion without resuming the human driver in the driving loop. With these results, the authors evaluated the impacts on safety of different levels of market penetration of the ACC system with the aggregate metrics for two groups of parameter settings:

- $T' = 1,1 \text{ s}$, $t'_a = 0,5 \text{ s}$ and $b'_m = 3,8 \text{ m/s}^2$

Which resulted in a reduction of TIT by 34 % and a reduction of TET by 39,7% for a 10 % market penetration. These values became 77,6 % and 67,8 % with a market penetration equal to 100 %. The safety gains seems to grow with market penetration, especially in the initial stages (under 30 % of market penetration)

- $T' = 1,1 \text{ s}$, $t'_a = 1,5 \text{ s}$ and $b'_m = 2,8 \text{ m/s}^2$

For this group of parameters, no improvements on safety were obtained.

Finally, the safety-related impacts of Variable Speed Limits were assessed. 9 variable message signs were virtually placed next the loop detectors in the simulations and were exploited to reduce the speed of the traffic flow upstream the congested front. With only the VSL strategy, TET decreased by 27,1 % and TIT by 28,8 %. When implemented with 10 % of ACC-equipped vehicles ($T' = 1,1 \text{ s}$, $t'_a = 0,5 \text{ s}$ and $b'_m = 3,8 \text{ m/s}^2$) these reduction grew by 8,4 % and 24,2 % respectively.

Future research directions pointed by the authors concerned the optimization of these parameters to achieve an optimal control effect as a function of the different traffic conditions. Moreover, Traffic Efficiency could be improved too with an appropriate tuning and these possibilities should be explored. Finally, another consideration that should be done is that in this work the lane change is not considered while assessing safety and the performance of the ACC system but a future integration in the simulations is explicitly mentioned by the authors.

Merat, N., Jamson, A.H., Lai, F.C.H., Daly, M. And Carsten, O.M.J., 2014. Transition to manual: Driver behaviour when resuming control from a highly automated vehicle.

In [42] a driving simulator was employed to assess the drivers' ability to resume control from a highly automated system. The time to carry out the take-over maneuver was studied and the visual attention towards the surrounding environment was evaluated by the means of eye tracking data. Two scenarios were compared at the end of the test, one in which the automation turned off on a regular time interval and one in which the take-over request was issued if the driver looked away from the road ahead for long time periods. These two scenarios are more conservative than the approach adopted, for example, by the Highway Chauffeur system that is going to be deployed in Italy within the C-Roads Italy activities and probably wouldn't easily be accepted by a human driver. These considerations fall out of the scope of [42] whose objective is to assess the drivers' ability to resume the driving task and not to evaluate a system deployable on the market. The authors report how, within the EASY project, the results showed

that with an L3 system engaged, the drivers' visual attention towards the road centre decreased, the same phenomenon occurred when a lane keeping system was engaged. A hypothesis expressed in [42] is that not only the level of automation affects situational awareness and visual attention but the same effects can depend on the type of automation support provided (lateral or longitudinal). Lateral support was found to diminish more visual attention. Besides, as long as the level of automation increases the time spent by the driver in engaging secondary tasks increases too. Because drivers suffered reduced workload while leaving the driving task to the automation and couldn't handle well sudden re-engagement request, the authors developed the driving simulation to not keep them out of the driving loop for long time. Therefore, the objective of this study is to determine if a solution based on eye and head tracking could be used to ensure that only attentive drivers would be supported by the automation, to understand which kind of approach resulted more effective (real time technique versus fixed intervals technique) and what time intervals were needed by the drivers to re-engage manual control. It is highlighted one last time how the Highway Chauffeur system considered in this Ex-Ante leaves an increased freedom to the drivers, the analysis of this work is important to evaluate what are the time intervals needed to re-take complete control of the vehicle.

During the simulations, 37 experienced drivers drove a vehicle cab in which both longitudinal (ACC) and lateral control (LKA) could be simulated. The ACC parameters set were a target speed equal to about 113 km/h and a time gap of 1.5 s not changeable by the drivers, an LCD panel showed when both the automated functions were activated. The event triggering the take-over request was the passage from three to one lane available (caused by a stranded vehicle or a road works), also signaled by Variable Message Signs.

In this scenario the two re-engagement strategies were implemented:

- "Fixed drive" requested the re-engagement of the driver periodically
- "Variable drive" requested the re-engagement of the driver using an algorithm and the faceLAB eye and head tracking cameras (identifying if drivers looked away from the road for more than 10 s)

To evaluate the test results, the "Percent Road Centre" PRC was employed, it is "(...) defined as the proportion of gaze data points, labelled as fixations, which fell within the road centre area, a 6° circular region located around the driver's most frequent fixation location". It is considered by the authors a sensitive indicator of visual distraction. The other metrics used were the mean and minimum speed held (for longitudinal control) and the lane position standard deviation to assess lateral control performance together with the number of steering reversal equal to 1° per

minute. Between the two approaches (Fixed and Variable drive) no difference in PRC were observed in value, only the pattern of fixations varied after the system disengaged from Fixed or from Variable drive (the former showing a steadier pattern).

The number of steering corrections was lower in the first 10 seconds starting from the re-engagement of the driver but increased in the time interval between 10 s and 35-40 s (a higher number of steering correction was achieved after the Fixed drive request and resulted in better lateral control). The authors concluded that the way the control is transferred from the system to the drivers affects their ability to resume control. Therefore, a well-designed HMI plays a fundamental role in the efficiency and safety of this transition. Besides, both lateral control and visual attention involved a time lag equal to 10-15 s for the driver to resume control after the disengagement of the system and their value stabilized after around 35-40 s.

“Understanding how to keep drivers in the loop during such automation, whilst allowing drivers to safely engage in other, non-driving-related tasks, is another important area in need of further research. Further research in this area is also needed to consider how the 30–40 s needed to resume adequate control of driving affects drivers’ situation awareness and ability to manage sudden or unexpected scenarios which, for example, may not be handled by the automated system, due to its limitations”

Forster, Y., Naujoks, F., Neukum, A. And Huestegge, L., 2017. Driver compliance to take-over requests with different auditory outputs in conditional automation

In [22] the impacts of two different auditory outputs supplementing the information provided by a visual HMI are analysed. The comparison is carried out between a generic warning signal and an information provided both by warning signal and by speech which, if provided correctly, should grant improved situational awareness and faster reaction times. The comparison is based on the results of simulated driving, during which the drivers were engaged in secondary tasks such as magazine reading. The system simulated was an L3 system. It should be highlighted how the authors explicitly mentioned the possibilities granted by V2X communications that could allow the HMI to provide the take-over request in advance (this is an important feature that is going to be analysed in the following paragraphs of this Ex-Ante and could greatly enhance both Safety, User Acceptance and Traffic Efficiency). The transition of control involves multidisciplinary fields and also psychological works should be investigated. On the basis of their bibliographical research, the authors stated that switching between two different tasks involves performance costs both due to the needed reconfiguration of the mental

task representation or to the persistence of the previous task mental configuration. The implementation of auditory inputs can enhance the information carried by the visual support granting omnidirectionality, for example, and the possibility to be perceived even if the driver is engaged in secondary tasks.

“Additional speech output could be very beneficial when a larger window of time is left to react to the particular system limit – which is precisely the benefit of cooperative perception technology (...)”

The authors highlighted a potentiality of the speech output which can reduce the necessity to look for a long time interval to the HMI to evaluate the situation, leaving more time to look at the road. Also, if speech inputs are provided to the driver, less visual information can be displayed on the HMI, lowering the visual workload. It should be evaluated, though, how these speech warning can impact on User Acceptance. The paper also mentions how, while exploiting V2X communications, it should be evaluated if drivers react better to non-critical scenarios in which no time pressure subsists and the take over times can be longer than 20 s (a message in advance granted by V2X communications can achieves similar effects).

The carried out evaluation between the generic warning signal and a speech warning signal was based on usefulness, visual workload, usability, acceptance and compliance defined by the author as the reaction time until:

- The first gaze was directed towards the road ahead
- The drivers put away the manual non driving related task and their hands were free
- The hands touched the steering wheel
- The CAD system was deactivated

During the driving simulations, the take-over could be realized by the drivers by pushing two buttons on the steering wheel, by braking or by applying a torque on the steering wheel. A longitudinal control similar to the ACC one was simulated with a target speed of 130 km/h and a time gap of two seconds. The take-over request was due to the appearance of yellow secondary markings and the emerging of a secondary lane, 20 s before reaching this critical section the drivers were signalled to retake back control of the vehicle.

The HMI turned orange from blue and a “soft” take-over request was displayed, after 7 seconds an “hard” take-over request was issued for 6 s. This visual strategy was adopted for both the auditory scenarios, the generic warning signal was provided by the means of two high frequency

warning tones before the announcement on the HMI while the speech signal was presented as a message stating “Unclear lane ahead, please take over soon”. In both scenarios three high frequency warning tones were issued before the hard take-over request.

The main metric used to evaluate the two approaches was the reaction time, composed by the gaze reaction (first glance on the road after the take-over request), time necessary for the hands to be freed from the secondary task, time necessary for at least one hand to be on the steering wheel and time needed to deactivate the system. User Acceptance was assessed too, by using the System Usability Scale through which the driver’s preference regarding the two system had to be stated and the perceived usefulness was evaluated on a 15 point Likert scale.

The results showed how with the “Speech + generic” auditory strategy most drivers took over in the announcement stage while with the “Generic” strategy the take-over happened after the soft take-over request was presented. No change in the gaze reaction was obtained between the two auditory strategies while shorter times necessary to put the first hand on the steering wheel were recorded in the “Speech + generic” scenarios, the same happened to the time needed to free both hands from the secondary task.

16 out of 17 participants preferred the “Speech + generic” input while the only one to favour the “Generic” solution wasn’t sure about the acceptance of the speech warning on the long term, when occurring too frequently.

Despite the improved reaction times, an interval of more than 4 s was needed between the gaze reaction and the first hand on the wheel, the drivers put the magazine away without hurry, nevertheless the time budget of 20 s resulted sufficient for a comfortable control transition. On the basis of their findings the author highlighted how the attention allocation was generally guided by the generic warning signal while the speech input helped the drivers in building an improved situational awareness (decreasing the time needed to free their hands from the secondary task and to put the first hand on the wheel).

Melcher, V., Rauh, S., Diederichs, F., Widroither, H. And Bauer, W., 2015. Take-Over Requests for Automated Driving

Yet another relevant work is [41] in which the authors studied the time needed to the driver to react to a take-over request issued at highway speed while approaching roadworks. The paper compares the performance of different support for the visual information (HMI together with the mobile phone or not) and different take-over modalities (with or without brake jerk). The automated system simulated could accomplish both longitudinal and lateral control, thus identifying with the Highway Chauffeur system that this first part of the Ex-Ante tries to define.

On the basis of the authors' bibliographical study two interesting values were reported in this study, 8,8 s as a sufficient transition time in traffic jam scenarios and a value equal to 8 s in a highway scenario. Therefore, based on their literature findings, a value of 10 s for the take-over task was evaluated, also considering the different input strategies simulated.

During the simulations, the secondary task carried out by the drivers was a quiz game, the take-over request was presented with an acoustic warning and a visual warning on the HMI, in some scenarios this visual information could be provided on the mobile phone, with or without an additional brake jerk. Some of the information presented by the HMI were:

- The automation scale which shows what automated function is active (none, longitudinal control or Highway Chauffeur)
- The automation monitor which shows the vehicle in its current situation
- The message field which shows the take-over request when issued

In the scenarios where the brake jerk strategy was implemented, a brake jerk was applied 1 s after the take-over request. In general, the result showed response time between 1.4 s and 6.7 s, proving the 10 s interval sufficient to carry out a transition of control from the automation to the human driver. The applied brake jerk didn't affect the reaction time but induced the drivers in accelerating rather than steering or braking while retaining control, 10 s was deemed by most of the drivers as an acceptable time interval but one third of them would have recommended longer transition times after the test. Two-thirds of the users perceived an increased safety when the take-over request was displayed on both the HMI and the mobile phone.

In the conclusion, the authors posed a relevant issue that should be faced: how to handle sleepiness and what time interval can produce safe take-over transitions in these situations.

Son, J. And Park, M., 2017. Situation Awareness and Transitions in Highly Automated Driving: A Framework and Mini Review.

This paper approaches the problem in a more general way, trying to define a framework to classify transitions in control between a L3 system and the human driver. As mentioned before and stated in this paper, a system that can carry out the whole driving task for long periods of time can provoke new kinds of accidents not bound to the automated driving itself but to scenarios in which the driver suddenly must retake control, because humans don't efficiently accomplish tasks that require vigilance for prolonged times. Issues arising in this scenario are, as already stated, complacency, mental workload, driver state and situational awareness (defined as the perception of the surrounding elements within a volume of time and space, their

comprehension and projection in the near future). An interesting classification is reported in this work, namely four types of transition:

- Driver-initiated, from the driver to the automated system
- Automation-initiated, from the driver to the automated system
- Driver-initiated, from the automation to the driver
- Automation-initiated, from the automation to the driver

The last one involves possibly safety critical scenarios and take-over times which the authors describe as function of the complexity of the surrounding traffic, the HMI design, the level of distraction of the human driver and driver's feature such as age and driving skills. The hypothesized take-over process goes from highly automated driving to manual driving through a transition phase composed by: situation awareness (perception, comprehension and projection) and decision.

On the basis of their bibliographical research, the authors state that the workload endured by the drivers with the system engaged is substantially lower compared to the one caused by the manual driving task, the shift to a sudden high workload situation involving reduced time available to respond to the take-over request is, therefore, critical. Other considerations from the authors based on their literature work are:

- A tactile feedback leads to faster responses from the drivers
- Visual-auditory warnings induced reaction times lower than the ones obtained with only visual warning
- Shorter available time intervals for the take-over transition lead to an increased percentage of accidents and to bigger longitudinal and lateral accelerations

Zeeb, K., Buchner, A. And Schrauf, M., 2015. What determines the take-over time? An integrated model approach of driver take-over after automated driving.

[64] aims to define what should be considered when evaluating the take-over time in response to an emergency situation. It should be noted that, even if many Day 1 C-ITS services are received in advance and, therefore, the driver is informed sufficiently earlier, some cooperative messages can have a more urgent nature (for example the one concerning the emergency vehicle approaching or person or animal on the road use cases). From their bibliographical review, the authors found values ranging between 2.1 s to 8.8 s for the take-over time depending, for example, from the driving task demands, the driver expectancy, the urgency of

the reaction, the automation complacency and age. Other factors could be traffic features, the equipped HMI, the secondary task involved etc.

“Hence, there is no such thing as a single, general take-over time”.

The focus of this paper concerns how visual distraction can affect the take over time during shifts of control from the automation to the human driver. Besides, motor readiness should be taken into account too, typical values considered from the authors are the following:

- Less than a second for reaction time
- 1.5 - 1.8 s for one hand to be put on the steering wheel
- 1.5 s for the foot to reach the brake pedal

Assumptions made are that the cognitive processing doesn't interfere with the motor readiness (and vice-versa) and that a relationship subsists between the gaze behaviour during the automated driving and the take-over performance. It is therefore important to assess how the drivers allocate their visual attention while out of the loop during automated driving and while engaging secondary tasks. The data considered in the paper are derived from an experiment conducted in the Daimler AD dynamic driving simulator where an automated system was simulated, with both longitudinal and lateral control entrusted to the automation. The maximum speed reachable by the ACC was set equal to 130 km/h, the time gaps varied between 2.5, 3.0 and 3.5 s, instead. No overtaking or lane changing maneuvers were allowed. Both visual and auditory signals informed the driver about the take-over request by the means of an acoustic warning and a red steering wheel icon. The transition of control was triggered three times during the simulation, twice by a roadwork or a road construction sign, 12 s in advance for the driver to re-engage the driving task. The third take-over request had a more urgent nature and was caused by a broken down vehicle perceived from the system about 50 m in advance, just after the preceding vehicle changed lane. With the three different values of kept time gaps and a preventive braking from the system, the time windows before the collisions resulted in 4.9, 5.7 or 6.6 s. Moreover, an evasive lane change maneuver was hindered from vehicles on the other lane, making a sudden brake from the human driver the only adoptable strategy to avoid collision. The secondary tasks that could be engaged from the drivers were texting and internet search, the movements of the eyes were recorded thanks to two cameras only during the three take-over transitions. Analysing the results, the authors considered not only mean values of the gaze behaviour but also extreme values that could be indicators of riskier behaviours, on the basis of these parameters the drivers were clustered in three classes: high, medium and low-risk drivers.

Once the take-over request triggered, the time needed to reach the steering wheel resulted, in average, equal to 1.14 s with a standard deviation of 0.45 s.

0.69 s were needed for the first gaze to reach the road, with a standard deviation of 0.2 s. Both the first hand on the steering wheel and the first gaze to the road were independent from the classes defined above. The performance of high risk drivers was different from the medium and low-risk ones when the time needed to start braking is considered. The values obtained from a one-way ANOVA were:

- High risk drivers (M = 2.31 s, SD = 0.67 s)
- Medium risk drivers (M = 1.86 s, SD = 0.67 s, $p = .038$)
- Low risk drivers (M = 1.63 s, SD = 0.5 s, $p \leq .01$)

Besides, an interesting comparison was made from the authors between the manual driving scenario and the automated one: while the duration of glances at the road lasted almost the same, the duration of the glances at the secondary task was more than 11 times longer during automated driving.

“Glance durations at the street, however, seem to be mainly unaffected. A possible explanation for this effect could be that the glances at the road have to be of a certain duration in order to adequately perceive the driving environment and to update the mental model of the driving situation”

Moreover, different strategies of attention allocation were performed by the drivers, some preferred many but short off-road glances while others, on the contrary, favoured fewer and longer glances at the secondary task. The authors concluded that the number and the maximum duration of off-road glances is a useful indicator about the driver’s behaviour and the related risks during take-over requests, resulting in a good predictor for the readiness to re-engage the driving task (still the author mentioned that other factors could affect this performance such as fatigue, experience, personality, etc).

M. Yanagisawa, W. G. Najm, and P. Rau. 2017. 25th International Technical Conference On The Enhanced Safety Of Vehicles (Esv). Preliminary Estimates Of Target Crash Populations For Concept Automated Vehicle Functions

In [35] a preliminary estimation of the target crash population that could benefit from automated driving is presented, on the basis of a methodology presented in [73] from the same authors. The automated function falling between L2 and L4 levels of automation are considered on the basis of five layers of crash information: crash location, pre-crash scenario, driving conditions,

travel speed and driver condition. The numerical results are derived from American databases and are not easily transferable to the European reality, still the approach is relevant to define another methodology to evaluate Safety. As mentioned before the approach derived in this Ex-Ante can be employed simultaneously with other assessment tools.

The authors considered the human errors related to recognition, decision, performance and non-performance just as in [32, 52], part of these crashes can be prevented entrusting the automation with the control (non-performance errors, intuitively, don't concern the automation, a robot can't be sleepy). In literature often is stated that, if the driver's flaws are out of the equation, about 93% of the actual crashes could be avoided, as highlighted by the authors, though, this estimation doesn't account for what level of automation or which functions can prevent said crashes, moreover the authors aimed to consider which target crashes overlap with L0-L1 functions already available. Besides, as mentioned often in this Ex-Ante, until full automation is reached in 100% of the vehicles on-public roads, new types of accidents can and will arise.

The safety-related benefits obtainable from L2-L4 functions listed in [35] are: an aid in driver vigilance, decreasing of the total driver workload, continuously scanning of the environment, protection from distraction and support to novice drivers. The authors considered many automated function while here, only the consideration related to the Highway Chauffeur will be reported, also referring to [73]. The crash locations that can involve an HC vehicle in its ODD are only highway roads while the pre-crash scenarios for both Highway Chauffeur and Traffic Jam Chauffeur system are defined as Rear-End, Drifting, Road Departure and Changing Lanes (in [73]). The driving condition concerns the environmental features in which the crash occurred, specifically: light, atmospheric conditions and the conditions of the roadway surface. All can contribute to the exit from the ODD and consequent safety-critical scenarios. Besides if both the Highway Chauffeur function and the Traffic Jam Chauffeur one are considered (like in this Ex-Ante) both high and low speed values must be taken into account. In the same fashion, being the driver still needed as fall-back solution, the errors related to the driving task can impact on safety and can't be completely prevented by the system (actually they can rise in number during the control transition, as stated above). Once defined the target crash population, [35] presents the estimation carried out by the authors, please refer to this work for the complete results. For this Ex-Ante purpose it was useful to expose how the crashes that should be considered in the evaluation of Safety can be reduced to the relevant ones in an organic and formalized way.

2.5. Overview of the expected impacts and implementation logic

As emerged from the previous paragraphs, the effects of a Highway Chauffeur system on the four impact areas considered (namely Traffic Efficiency, Safety, Environment and User Acceptance) aren't univocal but rather strongly change with the functional parameters chosen and the strategies implemented. The clearest example is represented by the longitudinal control and the possible time gaps settable in the ACC system. As emerged in 2.2., the Adaptive Cruise Control is born as a comfort system and isn't conceived to increase the efficiency of the driving regime, thus the resulting impacts can be both positive or negative. If the time gap values are higher than the ones assumed during manual driving (≈ 1.64 s [54]) a reduction in capacity is foreseeable and an increased number of cut-ins can also decrease the overall Safety and Environmental benefits. User Acceptance increases with higher time gaps, instead. Moreover, the settable time gaps are a choice of the OEM while the value effectively chosen lies in the hands of the human driver, thus making the evaluation work extremely difficult and the results aleatory (being bound to OEMs' choices, to regional and cultural features and to the characteristics of the human driver himself). In [54] simulations aimed at assessing the impacts of the ACC system alone were carried out for time gap values equal to 2.2 s, 1.6 s and 1.1 s, respectively among 31.1%, 18.5% and 50.4% of the equipped vehicles. The results showed that no relevant increase in capacity was obtained (from 2.200 Vehicles/hour/lane to 2.030 ÷ 2.100 vehicles/hour/lane). Notable values considered in this work are:

- Maximum acceleration and deceleration achievable: 2 and -2 m/s²
- More than 120 meters between the HC vehicle and the preceding one for the speed control mode to be engaged
- Less than 100 meters between the HC vehicle and the preceding one for the gap control mode

On the other hand, the possibilities granted by longitudinally automated vehicles can't be overlooked, as emerged for example in [32] in which the considered values for the time gap range between 1 s and 2.5 s. As in [54] the lateral control is not entrusted to the automation so the results must be considered accordingly, the impacts are, in fact, consequent only to the longitudinal automation and don't reflect the overall effects of HC vehicles among the traffic flow. The same can be said about the Traffic Jam Chauffeur function that is not evaluated in these studies. However, the results showed that a control strategy like the one implemented in [32] (that considers the state of the surrounding traffic flow and of the possible congestion ahead) can improve Traffic Efficiency yet for a rate equal to 10% of ACC-equipped vehicles in a three

lane scenario while, in a one-lane scenario, a portion of 30% of ACC-equipped vehicles is not enough to avoid the traffic jam formation. These results are derived from an ACC-based traffic assistance system that isn't tailored on the driver comfort and could not meet the OEMs' strategies, therefore it is important to understand what kind of implementation is going to be deployed in the near future for the Highway Chauffeur system. It should be defined, at least, if these solutions account for possible V2X or Cloud communications between traffic control centers and HC vehicles (with resulting adaptation of the driving regime, at least near critical section of the infrastructure). Moreover, it should be evaluated what safety critical degree can be reached with current and future requirements and standards defined for cooperative messages, especially about their robustness, validation and latencies.

In [57] two automated longitudinal control modes are examined. The one that doesn't account for external communications resulted from the simulations in a reduction of speed standard deviation by 54.7%, of fuel consumption by 27.9% and of the rate of excessive braking by 74.4%. Moreover, a reduction by 2.5% of the traffic throughput arose and the average speed decreased. If the possibility of external communications is considered, instead, the result of the simulations showed lower speed standard deviations (by 80.8%), lower fuel consumption (by 42.5%) and less braking events (from 8.58 per vehicle per km to 0.12 per vehicle per km). Moreover, the traffic throughput increased by 14.1%. In [42] a value of 1.5 s was considered to simulate an highly automated vehicle.

In [16] a macroscopic gas-kinetic traffic flow model is presented and evaluated through simulations that considered an ACC penetration rate equal to 100% and no differences between the control parameters. Again, no lateral control was hypothesized. The time gap chosen was equal to 1.2 s but the authors highlighted how values as low as 0.8 s could also be considered, reflecting a more aggressive driving behavior in the ACC-equipped vehicles. In all the simulated scenarios the traffic flow resulted as more regular with a fair share of ACC-equipped vehicles. It is important to note that more than one value of time gap can be used by the HC vehicles, both if the human driver can choose between a set of eligible values and if different OEMs implement different eligible time gaps. This means that the evaluator's work is made more difficult, it should also be considered that vehicles simply equipped with the ACC system and not with a Highway Chauffeur system can be present among the traffic flow and should be considered in the evaluations. Moreover, the Traffic Jam Chauffeur function has still to be properly evaluated in order to understand for what percentage of equipped vehicles among the flow an earlier fading of the traffic jam can be obtained (if it can really be obtained).

In [98] a rather wide review of the different control laws for an ACC system is carried out, considering constant space headway strategies, constant time headway strategies and variable time headway strategies. Moreover, simulations were carried out through the Aimsum software employing both the Gipps model and the IDM model (a notable input is the reaction time of an ACC-vehicle, considered equal to 0,1 s). The simulations considered time gap ranging from 0,8 s to 2 s and different levels of market penetration, the results are quite concordant with what emerged from the bibliographical review: the impact of ACC-equipped vehicles on the traffic capacity depends on the chosen time gap value and can be both positive or negative (the threshold obtained in [98] is a time gap of $1,10 \div 1,20$ s below which the capacity increases with the share of ACC-equipped vehicles in the traffic flow). Moreover, from ring-road simulations emerged that ACC-equipped vehicles (controlled through the IDM) are able to dampen arising shockwaves for market penetration levels equal or higher to 50%.

As far as the lateral control is considered, the impacts on the four impact areas can vary mainly on the basis of the aggressiveness characterizing the HC vehicle's maneuvers. This, in turn, depends on the control algorithms developed by single OEMs and can vary strongly between different Highway Chauffeur systems. To identify the possible impacts of a conditional automated vehicle, then, it is judged useful to consider the few field tests carried out or planned in the next years in Europe (referring to the measured impacts). Moreover, the academic papers in which an algorithm is developed and simulated to assess Traffic Efficiency or Safety should be considered too, even if many of these works focus on the development of the algorithm more than on the impact of the automated vehicle on the surrounding traffic flow. In [7], for example, an algorithm is presented, able to allow dynamic maneuvers for autonomous vehicles (lane changing, swerving and braking) and evaluated mainly in relationship to Safety. In fact, from simulations the system resulted able to face the following traffic scenarios: jaywalking pedestrian, sudden stop at high speed, high density traffic approaching a turn, car suddenly entering roadway, S-turns and Simulated City. In [20] the impact assessment of some of the automated functions developed within the AdaptIVe project is presented together with notable impacts that refers to a system automated both longitudinally and laterally. Moreover, different scenarios were considered while drawing this evaluation, e.g. closure of a lane, Stop&Go driving, motorway entrance/exit, lane change, overtaking and free driving. The Safety impact assessment was accomplished for the following scenarios:

- Cut-in, within which the overall safety benefit resulted equal to 83.1% for the single automated driving from the simulations

- End of a lane, within which a 14% reduction of accident was recorded
- Obstacle on the lane, within which the probability of avoiding an accident is equal to 28.3%
- Approaching traffic jam, within which the overall safety benefit resulted equal to 40.1%
- Motorway entrance, within the accident avoidance resulted in a safety benefit equal to 49%
- Rear-end accident, within which the automated vehicle suffered less accidents (in a range between 60 and 80%)

The Environment impact assessment gave back the following result:

“Traffic with only 10% penetration of automated vehicles creates almost exclusively situations in which the automated driving function interacts with a human driver. Hence, the automated driving function has to react to the oscillating longitudinal driving behaviour of human drivers. In contrast, the frequency of interactions between two auto-mated driving functions is much higher for a penetration rate of 50%. Therefore the speed differences between the vehicles decrease due to the harmonized driving behaviour of automated driving functions resulting in decreasing relative velocities between the vehicles. Hence, at higher penetrations the positive impacts of a constant traffic flow on the energy level becomes clear.” [20]

It seems relevant to analyze in depth how a generic control algorithm for the conditional automated driving can impact on the surrounding traffic flow. There can be mainly two effects, for example if the driving of the automated system is more conservative than the human driver behavior, the HC vehicle should perform fewer lane changing and overtaking maneuvers, thus increasing travel time and lowering the overall capacity of the road and Traffic Efficiency. If the vehicle maximizes the number of lane changing and overtaking, instead, exploiting its enhanced perception of the surroundings, it could impose an increased number of decelerations on the vehicles on the other lanes, thus fostering the propagation of shockwaves upstream the traffic flow (impacting both Traffic Efficiency and Environment).

Many of the considerations made above can be found to be valid also for lower levels of automation, in which part of the longitudinal and lateral control can be entrusted to the automation but the human driver still retains the authority without exiting the driving loop. A set of impacts arising from the conditional automation is bound to the take-over transition, instead.

In fact, having the human driver out of the driving loop entails the need for him to re-engage the driving task at some point and, as stated in 2.4., this necessity can be a challenge. If the warning is delivered with the wrong level of urgency, if the take-over time available is reduced or if the information provided to the driver is not complete enough for him to gain enough situational awareness, abrupt maneuvers (e.g. deceleration, braking, lane changing) can be performed and impact on all the four impact areas considered in this Ex-Ante evaluation. Therefore, it appears clear how the impact of a HC vehicle among the traffic flow are bound both to its ODD and to how often the driver is asked to take-back control (in [4] the Highway Pilot function is foreseen to be active during 10% of the driving for an average duration of 30 minutes, for example). This can represent an additional challenge for the evaluators that must consider the characteristic of the specific Highway Chauffeur system tested when interpreting the results. The same difficulty can be encountered when considering the strong dependency of the abruptness of the maneuvers on the warning delivery strategies considered, the HMI designed and the characteristics of the human drivers.

In [39] the time to re-engage the driving task is considered short if lower than 3 seconds, medium in a range of 3 ÷ 10 seconds and long in a range of 10 ÷ 30 seconds. In [42] the simulations of a highly automated vehicle showed how, in the first 10 s, a lower number of steering corrections was performed by the driver, reflecting a worse lateral control that stabilized between 10 and 40 seconds from the take-over request. The two re-engagement strategies simulated were a “Fixed drive” request and a “Variable drive” request, the former re-engaged the human driver periodically while the latter issued a warning if the driver looked for more than 10 s away from the road. In [22] a take-over time of 20 s was considered because judged enough to characterize a non-critical scenario in which no time pressure subsists. The results of the simulations carried out in [22] showed that a “Speech + generic” warning improved the reaction times of the human drivers compared to the “Generic” solution, moreover, more than 4 seconds were needed to pass from the gaze reaction to the first hand on the wheel. In [41] the authors mentioned the values of 8.8 s and 8 s as enough to guarantee a safe control transition in a traffic jam scenario or in a highway scenario, respectively. In this study the simulations showed how a take-over time of 10 seconds was sufficient to carry out a transition of control. As stated in [64], though, a general take-over time can't be defined because dependent on many factors (i.e. HMI, warning delivery strategy, human driver's characteristics, traffic features, secondary task engaged, environmental conditions, etc.).

All these factors should be considered when designing and interpreting field tests because influence the abruptness of the maneuvers carried out as a reaction by the human driver and,

therefore, the impacts on the four impact areas. This inherent aleatoricity can prove to be challenging if different field tests are going to be deployed across Europe, as strongly advocated in the previous paragraphs, because the comparison of the results can be made difficult (especially if different take-over strategies are implemented in each field test).

In the following, a general overview of the results concerning both expected impacts and operational parameters of the system is reported

Some of the results arising from the bibliographical review		From field test and/or testbed	From modeling works	Research Effort
Potential capacity increase/decrease	$(- 2,5) \div (+ 7) \%$	✓	✓	+
Impact on the surrounding vehicles	Up to 20 vehicles	✓		+
Take-over times	$3 \div 10 \text{ s}$	✓		++
Reduction of safety critical scenarios cut-in related	Up to 83,1 %		✓	-
Reduction of safety critical scenarios while approaching an obstacle	Up to 28 %		✓	+
Capacity increase for headway lower than:	$1,10 \div 1,20 \text{ s}$		✓	++
Decrease in acceleration variances	$44 \div 52 \%$		✓	+
Potential fuel savings	$0 \div 28 \%$	✓		-
Time needed for a steady lateral control after the take-over transition	Up to 40 s	✓		+

Market penetration able to affect the traffic flow	$\approx 5 \div 10 \%$		✓	-
Operational parameters		From field test and/or testbed	From modeling works	Research Effort
TTC safety critical value	1,5 s	✓	✓	++
Feasible time gaps	$0,8 \div 2,5$ s	✓		++
Traffic Jam Chauffeur Speed range	$0 \div 60$ km/h	✓		++
Operational speed range	$0 \div 130$ km/h	✓		++
Overtaking and lane changing	Carried out by the system	✓		+
Lane marking presence	Mandatory	✓		+
Weather conditions	Clear, possibly wet surface	✓		+
ACC reaction time	$0,1 \div 0,4$ s		✓	+
Distance from the preceding vehicle that triggers the speed control modes	$100 \div 120$ m	✓	✓	+

It should be noted that this table is a summary of the analysis carried out in Chapter **Errore. L'origine riferimento non è stata trovata.**, thus the ranges of values can be rather wide, being the results of different studies using different methodologies and various boundary conditions. Moreover, the strength of the results is reflected in the research effort column, in which (++) is

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

Derived theoretical framework
Longitudinal control and ACC solutions
Lateral control and algorithms
Perceiving system
Operational Design Domains
Cut-in behavior // Ramp interactions
Safety assessment - methodologies
Best practices and applications around the globe
Possible modeling works and research directions

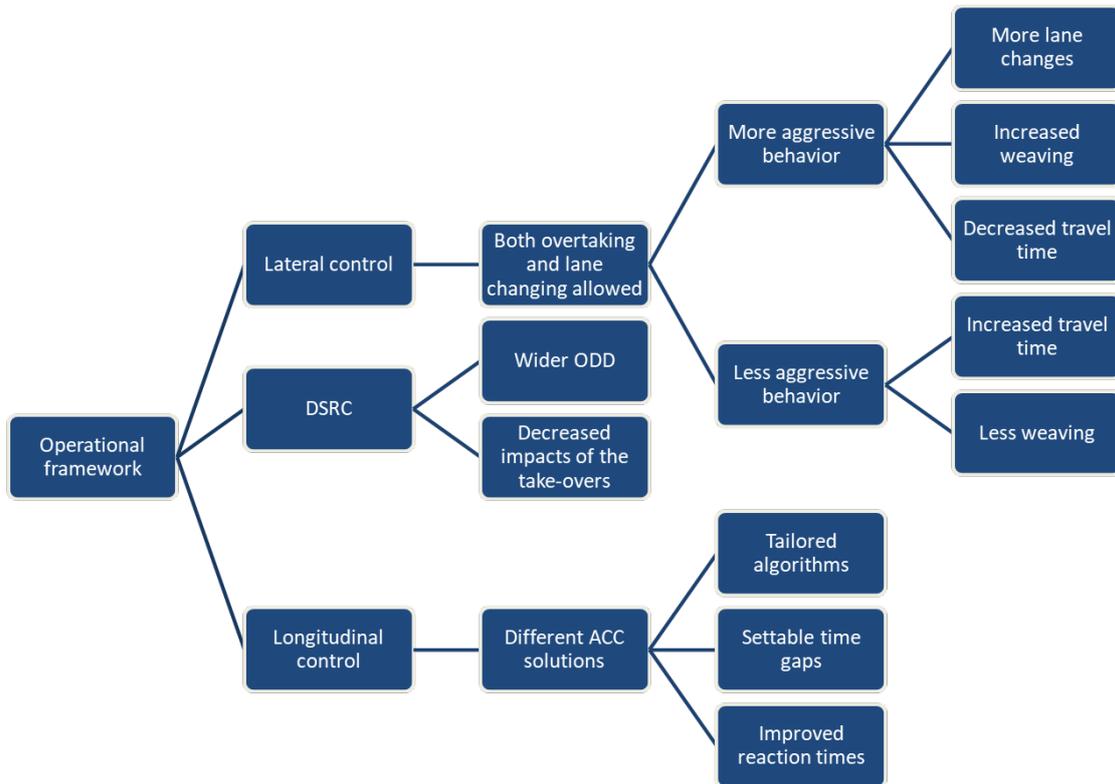


Figure 2: Operational and theoretical framework

3. Highway Chauffeur impact evaluation

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

- Traffic Efficiency
- Safety
- Environment
- Overall and User Acceptance

It should be noted that a distinction has been made between User Acceptance and Overall Acceptance, the former being related directly to the driver of the HC vehicle while the latter is related both to the human driver of the HC vehicle and to the drivers of the surrounding vehicles. The scenarios considered will concern an HC vehicle equipped with, at least, ACC, Lane Keeping Assist, Lane Change Assist, an Autonomous Emergency Braking system, and the perception system described in the precedent paragraphs. Also, the possibility to receive all the cooperative messages V2V and V2I (by the means of the messages standardized in the ETSI documents) is considered. How these messages are exploited by the system is still an open subject, being extremely bound both to the features of an OEM's product and to the current status of the international standards concerning the robustness and the reliability of these communications. In order to maintain a certain degree of generality, in this Ex-Ante some of the research questions consider the possibility that the inputs granted by V2X communication are directly processed and managed by the L3 system. It should be highlighted, though, that this hypothesis is more relevant in the medium-long term than in the short-medium one. As stated before, in fact, it is possible and likely that the current C-ITS standards won't grant performances high enough to allow the deployment of applications, on public roads, that could compromise functional safety, as defined in the ISO 26262.

Another relevant consideration that must be made is that, for the evaluation of the Highway Chauffeur system, the following hypothesis has been made: *the percentage of HC vehicles in the traffic flow reaches a level high enough to exercise an influence on the overall traffic flow.* For each scenario the inputs and outputs required to assess the impacts will be highlighted, both for field tests and for simulation works. The followed approach is based on "Research and Sub-Research Questions" and follows FESTA Handbook (FOT-Net 2017):

- Examples of Research Questions: How is the Highway Chauffeur expected to impact on traffic flow while engaged and in its ODD? How is the take-over maneuver

accomplished? Does the behaviour of other road users changes while interacting with an engaged HC vehicle?

- Examples of Sub Research Questions could be “How does the HC vehicle interpret and respond to the interaction with other vehicles?” or “How is the HC vehicle affected by the surrounding traffic flow (and vice versa)?” The changes of the parameters that characterise the traffic flow/HC driving are investigated for each relevant maneuver and situation; data requirements are mentioned; the suggested metrics are based on the Highway Chauffeur bibliographical review performed in chapter 2 or derived from dedicated works such as [52,74].
- Suggested methods and tools to quantify the effect of a certain percentage of HC vehicles on the impact areas listed above are mentioned, referring to the bibliographical review in chapter 2. Parameters needed as output and how to potentially measure them will be described, suggestion about the field test designs will be offered (i.e. while designing a field test on public road, an operational domain should be clearly defined following guidelines like the ones in [39, 45, 60], and fall-back strategies, like the one in [4], should be evaluated and assessed in advance).

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

How to investigate in depth each scenario, which data requirements meet and output indicators measure is left to choose for the evaluator as function of the test specificities and of the regional features. Besides, it should be noted that these evaluation guidelines have been designed to be applicable in general scenarios and are not referred to specific field tests or modeling works carried out in the C-Roads Italy activities (during which there will certainly be field tests but not every subject listed in the following paragraph will be evaluated).

Please note that the modal form “should / should not” is employed in this paragraph to indicate recommendations and suggestions, therefore no mandatory value should be given to what is stated.

“The introduction of supervised automated driving is posing new and specific questions (...), in particular since the automated driving functions do influence not only a certain defined scenario (for example accidents, near accidents, or safety related situations) but the whole traffic flow. These aspects are not sufficiently covered by existing evaluation methods and approaches. Hence, new comprehensive approaches are required.” [20]

3.1. Traffic Efficiency

Research Question: How conservative is the automated system? Does the longitudinal control law take into account strategies aimed at enhancing the traffic flow?

As mentioned in Chapter 2, the impact of the ACC on the traffic flow can be both positive, null or negative depending on the percentage of HC vehicles in the traffic flow and on the operational parameters set for the ACC functioning. Unlike the CACC, designed mostly to reduce headways, thus increasing road capacity, the ACC system was born as a comfort function and can involve, especially in the short term and for inexperienced drivers, time gaps similar to the ones kept by human drivers. Besides, keeping the driver out of the driving loop can lead to more conservative driving styles and increased travel times, thus worsening the infrastructure capacity (the cost bound to the travel time is perceived decreased by the human driver that is engaging a secondary task). In fact, if the cost related to travel time perceived by the driver is low, OEMs could favour safer control laws penalizing overtaking and lane changing maneuvers, especially in the short term. On the other hand, if the possibilities granted by V2X communications and dynamic gaps are exploited, enough HC vehicles in some sections of the road can enhance the traffic flow and delay congestion. Moreover, more efficient braking and restart during traffic jams can foster the return to decongested states (although not in the same fashion of the CACC).

➤ *Does the HC system avoid lane changing and overtaking, when unnecessary?*

When the driver is out of the driving loop and can engage secondary tasks, the time is no longer perceived as lost and a more conservative driving style can be accepted. If the HC vehicle’s algorithm is not as aggressive as the human driver would be, lane changing and overtaking maneuvers can be reduced and result in an increased travel time and in a decrease of the overall Traffic Efficiency.

➤ *Are the lane changing maneuvers carried out in a more efficient way?*

On the other hand, if the system avoids sudden lane changing maneuvers, it doesn’t produce perturbations and shockwaves upstream, de facto nullifying the flaws of the

human driving bound to lane changing and overtaking. It should be noted that the distinction is not, inevitably, between sudden lane changing maneuvers and no lane changing maneuvers; if the HC is designed accordingly, the lane changing maneuvers can be carried out in a way that no sudden braking is imposed on the following vehicles, overall performing fewer but smoother lane changes. In [2], for example, is stated that the time required for a lane change results more uniform for the automated driving systems tested in the AdaptIVe project. Depending on the driver aggressiveness reachable by the algorithm, lane changing maneuvers can be carried out more or less frequently by the HC vehicle. In both the scenarios, the HC vehicle can exploit its environmental perception system to start the maneuver when the available space on the other lane is wide enough, in a smoother way, avoiding sudden braking from other vehicles (and resulting perturbations upstream). On the other hand, a system designed to minimize travel time, instead, can carry out these maneuvers whenever the space on the other lane is wide enough to ensure safety, imposing braking on other vehicles just like a human driver in a hurry would do (or even more). It should also be assessed if the HC vehicle can finish every started lane changing maneuvers or if some of these are aborted mid-way (this would involve completely useless perturbations in the traffic flow).

- *Is the ACC time gap favourite by the drivers higher, lower or the same as the one characterizing human driving?*

Granting full control to the automation, even if for limited amounts of time, can reduce the feeling of safety among the drivers. If that is the case, they could choose to keep a distance from the preceding vehicle even bigger than the one they would keep while in control. An increased time gap leads to increased distances from the preceding vehicles and therefore to lower road capacity. Moreover, increased headway values can encourage overtaking maneuvers and cut-ins from external vehicles, which result in perturbations upstream the traffic flow. It should be considered that an efficient braking from the HC vehicle remains a braking maneuver and the vehicle behind the HC one must brake a little harder in response. Besides, an ACC-equipped vehicle can be more prone to perturbations caused by external vehicles cutting in because, in order to ensure the safe time gap, it automatically brakes in response.

- *Is the HC vehicle's longitudinal control overall more efficient than the human one?*

An automated system is constantly scanning the environment, without distractions or lack of attention, reaching a state that could be described as an “improved situational awareness”. This increased attention to the road and to the other road users should decrease the number of sudden maneuvers in response to the other vehicles, especially sudden braking resulting from a temporary lack of focus. This, in turn, should foster an increased traffic efficiency.

- *Does the HC vehicle adapt its time gap value while approaching highway entrance ramps?*

In literature, different works face the issue of the interaction between the HC vehicles and human driven vehicles entering the main branch through an on-ramp (e.g. [28]). It should be assessed if the algorithm controlling the HC vehicle is able to interact with the approaching vehicles, understanding their possible intentions about yielding and adapting its speed and time gap accordingly. If the algorithm understands earlier the intentions of the other vehicle, it should be able to adapt the driving style of the HC vehicle in a smoother way, thus impacting less the traffic flow upstream. Besides, if the two conflicting vehicles are able to exploit V2X communication, cooperative merging can be used to define the speed values and the time gaps needed to increase the efficiency of the merging maneuver [2].

- *Does the system exploits information from traffic control centres or other external service provider to adapt its driving regime and ease the traffic flow?*

In a logic similar to the one that inspired [32], if a sufficient number of HC vehicles receives indications through V2X communications about the most efficient driving strategy or can evaluate it from the information perceived through their sensors, a more efficient traffic flow can be achieved tailoring the control parameters according to the traffic conditions. The time gap is not the only parameter that can impact traffic efficiency, calibrating the HC vehicles speed through V2X communication can help reduce congestion too (this concept is going to be faced in detail in the paragraph dedicated to the use case: dynamic speed limit). Another work that considers this kind of strategies is [20], in which the adaptation of both speed and time gap before approaching ramp areas is considered (in relation to environmental and safety-related impacts).

- *When the ODD is left, does the take-over transition happen in a smooth way or does the driver act in an abrupt way, performing sub-optimal maneuvers?*

When the transition in control must be accomplished, it is important that the driver has enough time to re-evaluate the situation and to understand what maneuver must be performed in response. If the take-over time is too low or the message is delivered with a pointless urgency, the driver can perform sudden maneuvers (such as lane changing or braking) that affect the surrounding traffic flow, generating shockwaves and perturbations upstream.

Research Question: Does the Traffic Jam Chauffeur ease the traffic congestion, promoting an earlier return to the decongested state?

While the Traffic Jam Chauffeur is designed to ensure safety and comfort, an important automation feature can be exploited, especially when the traffic jam lasts for long time: the Traffic Jam Chauffeur doesn't get tired, which means that an efficient stop and go regime is kept as long as the traffic jam lasts. Accomplishing both the braking and the accelerations in the most efficient way should foster the return to a decongested traffic state, even if not in the same fashion as in the CACC systems.

➤ *Does the Traffic Jam Chauffeur decrease the number of rear-end collisions, thus enhancing the overall Traffic Efficiency of the system?*

Especially when the traffic jam doesn't fade for a while, the support provided by the automated function can prevent the HC vehicle from colliding with the preceding vehicle. Besides, an HC vehicle should be able to respond in the most efficient way to a sudden braking from the preceding vehicle, decreasing the odds of being hit from the following vehicle. Avoiding collisions enhances the overall performance of the system and Traffic Efficiency.

Assessment instrument

The impacts of the Highway Chauffeur system on Traffic Efficiency can be assessed both through field tests and modeling works (for which some literature works can also be considered [16, 32, 54, 57]). A field test can be used to validate the effective ODD of the system implemented and to obtain some "behavioural" outputs that can assess the capability of the system to interact with the surrounding traffic flow. Another important result could be the propensity of the human driver to override the system, if for example its level of aggressiveness is judged as inadequate to the human demands. Modeling works can, then, use these outputs to evaluate the impacts on the overall traffic flow, in different scenarios and with different levels

of market penetration (one of the main focuses should be the assessment of the impacts related to the ACC parameters).

The evaluation of possible traffic optimization strategies based on optimal speed values and triggered by a TCC or through V2X communication is going to be described in the dedicated use case (4.2.1. Dynamic Speed Limit Information).

3.2. Safety

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

Other road users can wrongly guess the situation, especially in the short term when the technology market penetration is limited. This could lead to unpredictable behaviour and, consequently, to unsafe or dangerous situations. Besides, the HC vehicle itself can interpret wrongly the behaviour of the surrounding traffic and act accordingly, putting itself and other road users in danger.

- *Do the other road users understand that the driver of the HC vehicle, engaging a distracting secondary task, doesn't represent a threat for their safety?*

Seeing another driver that reads the newspaper or plays with their mobile phone can have a threatening effect on the surrounding drivers which could engage evasive maneuvers or react inappropriately and with an urgency that isn't warranted in reality.

- *Does the HC vehicle perceive all the elements characterizing the surroundings? Is it able to interpret their intentions and draw an almost exact future scenario?*

In order to react accordingly to the inevitable changes like the ones characterizing a dynamic task like driving, the HC vehicle must be able to correctly perceive the surroundings in each scenario included in its ODD. Besides, this perception must be exploited to evaluate which trajectory must be adopted and what inputs must be transmitted to the lower control level. Therefore, the intentions of the surrounding traffic must be evaluated and the ability of the system to do so must be assessed. The HC vehicle should prove to be able to react to "last-minute" adjustments of the surrounding

vehicles' maneuvers or to initial estimation errors, even resorting to sudden and abrupt maneuvers.

- *Does the number of possible pre-crash scenarios increase or decrease when the HC system is engaged in its ODD?*

Even if the HC system results able to react to “last-minute” adjustment from other vehicles or to initial estimation errors regarding their intentions, an increased number of safety-critical situations and, for example, low values of TTC could arise. Thus, it should be evaluated how often these critical values are reached while driving with the HC system engaged (depending both on the automated system capabilities and to the surrounding traffic behaviour). This kind of evaluation should be carried out in order to compare the system overall level of safety to the one achievable by the human driver in road sections that falls in the system ODD.

- *Are the lane changing maneuvers carried out in a safer way thanks to a more conservative approach or to an enhanced environmental perception?*

Compared to maneuvers carried out by a human driver, the one accomplished by the system can be fewer and started only when a wide space is detected on the other lane. A more conservative approach should reflect on fewer sudden maneuvers and, consequently, on a decreased number of harsh braking on the other lane. In the same fashion, the equipped sensors should guarantee a continuous awareness from the system concerning the surrounding traffic, allowing the HC vehicle to exploit every gap on the other lane as long as it is deemed as safe and efficient.

- *Does the Highway Chauffeur system impact on the number of rear-end collisions?*

By the means of the ACC, the time gaps between the HC vehicle and the preceding vehicle can be reduced. Scenarios could arise in which the HC vehicle finds itself more prone to rear-end collisions because it can only guarantee braking action as soon as the time gap reaches a certain threshold. It should be evaluated if the system can guarantee safety in the most critical scenarios for the lowest feasible time gap that can be set, taking into account for example emergency braking in the preceding vehicle and/or reduced adhesion on the road. It should also be noted that the impact of a fair share of HC vehicles among the traffic flow can possibly be positive, decreasing the number of front-end collisions, as stated in [102].

- *Is the vehicle more prone to collisions due to increased time gaps from the preceding vehicles and resulting cut-ins from external vehicles?*

On the other hand, if the time gap set is wide enough, vehicles from other lanes or overtaking ones are more likely to cut-in in front the HC vehicle itself. These maneuvers can involve critical values of TTC or other safety-related metrics and lead to collisions, especially if the Highway Chauffeur system fails to interpret the surrounding situation in time. However, as for example showed in [20], an automated system can also respond in a safer way to these maneuvers, the simulations carried out within the AdaptIVe project resulted in a safety benefits equal to 83.1% in the cut-in scenario, indeed.

- *Does having the Highway Chauffeur system engaged on highways prevent over speeding scenarios and related crashes?*

If the Highway Chauffeur system is engaged, the maximum feasible driving speed is the one mandatory on the road section travelled. In fact, one of the requisites for the automated driving to be feasible and legal on public roads is the compliance of the system with the legal framework and the mandatory regulations. Therefore, if the driver engages the system he or she must accept this limitation and settle for the maximum legal speed value. Having the system engaged for a fair share of kilometres on highways and for a certain percentage of vehicles among the traffic flow should prevent the accidents caused by over speeding. As reported in [77], both the number and the severity of crashes increases with the driving speed on a road section, indeed.

Research Question: In case of safety-critical scenarios, is the fall-back strategy of the HC vehicle able to avoid collisions?

In a dynamic environment like the driving one, the system ODD can be violated with very low notice. Thus, the human driver could be found unready to retake control and react to a sudden environmental changes. If that is the case, it should be evaluated how the system reacts to these sudden events (for example, by the means of a degradation cascade as mentioned in [4]) until the driver is finally ready to re-engage the driving task. Even when the ODD exit is known by the system some time in advance, the take-over process should be evaluated on the basis of the designed HMI, the notification system and all the other variables presented in 2.4. Lastly, the ability of the system to respond to a sleepy, inattentive or incapacitated driver should be assessed.

- *Does the system detect an error in its estimations of the future states with sufficient advance to avoid collisions? How often a similar error happens and how often critical values of safety related metrics are reached?*

The evaluation of the surroundings while defining the optimal feasible trajectory of the HC vehicle must face issues such as computational complexity, unpredictability of the human behaviour and sensor noises. If a last moment adjustment is needed in the vehicle's trajectory, the system ability to carry out such adjustment should be evaluated together with the frequency and the efficiency (through the recorded metrics) of these adjustment.

- *What kind of temporary fall-back strategy are designed to grant the driver with the possibility to re-engage the system even when sudden events happen?*

The ability of the system to react to sudden exits from its ODD should be evaluated, focusing on the most likely scenarios such as sudden meteorological events or system failures, for example. Moreover, for each achievable situation state [4], the safety level should be evaluated and judged acceptable or not, in relation with the corresponding probability of occurrence.

- *How the system reacts to a not-reacting driver? Does it take the vehicle to the nearest safe state with an acceptable level of safety?*

A sleepy driver, for example, could need take-over times much greater than the ones designed in the L3 system while the prospect of a long highway journey could induce some drivers in drink&drive behaviour, resulting in a hindrance to their perception capabilities. Moreover, some sort of sudden illness can incapacitate the driver while the HC vehicle keeps travelling. Therefore, while the driver is the standard fall-back option for an L3 system, he can't be always relied upon and the HC system may be designed to handle these situations with the lower achievable risk. If that is the case, the fall-back strategies should be evaluated in their capability to take the vehicle to the nearest safe state without involving the surrounding road users.

Research Question: Does the transition in control happen in a safe and reliable way? Is the take-over time enough for the driver to re-engage the driving task in the most critical scenario?

When the HC system detects that it is going to be no longer in its ODD, it issues a warning to the driver, sufficiently in advance for him to take back the control. This shift in control can be one of the most challenging maneuver during the route, if the information is delivered in a wrong or unclear way or if the driver doesn't behave as expected.

- *Does the driver understand correctly the received information, what he is expected to do and what is the urgency of the necessary actions?*

Depending on the type of message delivered and the possible presence of auditory warnings or haptic supports, the driver's attention can be addressed towards the designed interface and the delivered message. From the inputs received, the driver must be able to understand quickly the current situation, the cause that led to the system disengagement request, the actions that must be undertaken and the urgency of such actions. This last element is not to be overlooked, because an excessive hurry can lead to sudden and dangerous maneuvers while underestimating the warning can lead to slower responses and collisions.

- *Is the available time sufficient to let the driver completely stabilize both its longitudinal and lateral control?*

As described in the previous chapter, the take-over time can vary strongly between different scenarios and also between different human drivers and their driving and cognitive skills. This means that, when taking into account the enormous quantity of possible take-over scenarios, the designer must make the HC system able to guarantee minimal values of take-over time deemed safe for almost each possible driver. This requires both an enhanced perception system able to detect in advance the exits from the ODD and a well-designed HMI able to minimize the time needed to rebuild situational awareness and motion readiness. It is therefore important to evaluate how the needed take-over times vary with the surrounding scenarios and with the driver's features, it should also be assessed how much time is needed to completely re-engage both longitudinal and lateral control depending on the secondary task carried out by the driver. For example, if the lane is going to narrow because of roadworks ahead, the time needed for the driver to completely stabilize his steering action (nullifying oscillations) becomes rather important and isn't limited to the first seconds necessary for him to take his hands on the steering wheel and re-engage the lateral control.

Assessment instrument

The Safety evaluation should be done mainly through modeling, bibliographical reviews or validation procedures, but can't be complete without field tests able to evaluate the designed system and how it interacts with the surrounding traffic. The capability of the Highway Chauffeur system in responding to unforeseen scenarios and sudden maneuvers carried out by the road users should be assessed with a huge number of kilometres driven. In designing these tests on the road, guidelines like the ones drawn from the NHTSA can be considered; in [45], for example, the main safety-related design aspects to be considered when deploying automated systems on public roadways are listed. Besides, field tests or virtual testbeds can be employed to assess behavioural inputs to design appropriate car following models and safety critical scenarios in modeling works. Other behavioural subjects that can be investigated, even with more local or restricted field tests, concern the transition of control between the HC system and the human driver, take-over times and the relationship between the two authorities on-board (the human driver and the Highway Chauffeur system). It should be noted that not all the feasible fall-back solutions must be implemented, for example an HC vehicle could be not equipped with systems that monitor the driver's sleepiness or the alcoholic level in its breath. In the same way an HC vehicle can be designed to function both with auditory and haptic warning or only through one of them. If a function is implemented, though, it should be evaluated. Besides, pre-crash scenarios and critical situations can be evaluated through field tests or modeling works and employed to evaluate the overall safety of the system (as suggested, for example, in [66]).

The data collected should also be relevant to investigate any incidents that may occur (achievable through Event Data Recorders) and the pre-crash scenarios detected (on the basis of the safety-related metrics) should be recorded. The study of pre-crash scenarios could be an alternative solution to the evaluations based on information on detailed accidents that, as stated in [20], often aren't available. Approaches in this direction have been presented, for example, in [35, 73]. To assess the impact of fewer over speeding vehicles among the traffic flow both Nilsson's Power Model and an exponential model can be employed [77].

3.3. Environment

Research Question: Does an HC vehicle consumes more or less fuel while autonomously driving in its ODD (when compared to the same road section driven manually)?

- *Does a more efficient longitudinal control foster a decrease in fuel consumption?*

On the basis of what has been stated in chapter 2 (or what can be found in literature, e.g. [10]), when the ACC is engaged both the accelerations and the decelerations carried out by the system can be considered smoother and more efficient than the ones performed by the human driver. In fact, especially during long highway journeys, tiredness or distraction can worsen the driver performance, thus increasing the number of abrupt maneuvers aimed at responding to the driving regime of the preceding vehicles. Besides, if the driver is not involved in the driving loop, a more conservative driving styles could be performed by the HC vehicles, resulting in a lower number of overtaking maneuvers (and a lower number of the resulting accelerations and decelerations).

- *Do the maneuvers carried out by the HC vehicle have a reduced impact on the surrounding traffic, imposing fewer and smoother braking and hindering sudden and energy consuming maneuvers?*

As described in chapter 2, depending on the driving aggressiveness of the system the lateral control can involve more or less lane changing maneuvers, carried out both in a smoother or sudden way. This means that a HC vehicle designed to reach its destination in the shorter feasible time will perform a similar number of lane changes when compared to the human driving while a more conservative approach implies a reduced number of lane changing and overtaking maneuvers (with the resulting reduction in fuel consumption both in the HC vehicle and in the surrounding vehicles). In both scenarios, though, it can be foreseen that the lane changing maneuvers will be started only if the perception system of the HC vehicle judges the time gaps available on the other lane to be wide enough, thus limiting the number of harsh and sudden braking imposed to the following vehicles.

- *Do traffic management strategies that exploit the presence of automated vehicles on the road prevent or reduce congestion?*

As mentioned in chapter 2 and often stated in literature, having a fair share of automated vehicles on a road section can ease the traffic flow, reducing or delaying congestion events. This becomes possible if some form of damping function is implemented in the algorithm and triggered by the perception system or V2X communications. The overall effect on congestion depends on the ACC parameters set and the level of market penetration.

- *Does the Traffic Jam Chauffeur foster a more efficient Stop&Go driving? Does it favour an earlier return of the traffic flow to the decongested state?*

As mentioned in the previous paragraphs, a durable traffic jam can tire the drivers and degrade their driving abilities, resulting in more abrupt decelerations and accelerations and worsening the perturbations caused by the Stop&Go driving. Automation, in turn, can face hours of traffic jam still retaining the same regime of accelerations and decelerations, thus fostering an earlier return to the decongested state. Even when the traffic jam doesn't last hours, the Traffic Jam Chauffeur should perform a driving regime more efficient than the average human driver, according to the same principle that sees the automation driving more efficiently than the human driver.

- *Is the take-over maneuver carried out in a smooth way or the driver re-engage the driving system imposing sudden and abrupt braking?*

Strong braking actions due to the perceived urgency or to a decreased situational awareness have an impact both on the fuel consumption of the HC vehicle and on the fuel consumption of the surrounding vehicles that must adjust their driving accordingly.

- *Does the HC driving style synergize with the electric vehicle's technology, assuring a more energy-efficient driving behaviour?*

In literature is often stated that plug-in electric vehicles are perfect candidates for the automation. For example, in [10] is stated that "PEVs are inherently well suited for automation thanks to their drive-by-wire controls and electric actuation systems", in [29] that "[...] the electrification of vehicles is expected to leave space for synergies with an idea of automation of transport", while in [44] is reported that "(...) autonomous vehicles support electric propulsion by better managing acceleration, cruising, slowing, and stopping. Automatic computation of driving profiles for power and brake application assists drivers to maximize efficiency and range". Therefore, both technologies in the medium term can enhance each other, promoting a faster deployment and resulting in huge environmental benefits. In the short term and in a single field test it should be evaluated how the automated driving decreases the energy consumption of an electric vehicle, instead.

- *Is a driver out of the driving loop encouraged to let the HC vehicle choose the most energy efficient route, even if a little bit longer?*

As stated for example in [44], an automated vehicle can select the most energy efficient route because the passengers (or the driver) involved in secondary tasks can accept

easily slower accelerations, lower speed values and, also, slightly increased travel times. This phenomenon impacts both on the single vehicle's energy consumption and on the overall traffic flow (allocating in a more efficient way the vehicles on the network and easing congestion). Other examples of automated vehicles able to adopt the most energy efficient driving behaviour can be found in [2], where a “predictive automated driving to reduce fuel consumption” was implemented.

Assessment instrument

Different ACC parameters and motion planning algorithms can result in different values of fuel consumption. To assess this value, different scenarios should be evaluated, considering also how the interaction with the surrounding traffic flow changes with the ACC parameters and the maneuvers carried out. From field tests on public roads behavioural inputs can be evaluated and employed in following modeling works aimed at assessing different market penetrations and traffic control strategies or impacts in the medium and long term.

As stated in [20], the results of the environmental assessment depend also on the behaviour of the automated (or semi-automated) vehicle that differs between different OEMs.

3.4. Overall and User Acceptance

It should be noted that Acceptance is extremely bound to the characteristics of the specific OEMs products, of the designed HMI and of the HC vehicles' features. In this paragraph only the more general aspects will be analysed, leaving to future evaluation works the task to evaluate Acceptance bound to specific implementation schemes, products and Service Providers.

Research Question: Do the surrounding road users feel threatened by an HC vehicle in which the driver is showily engaged in distracting secondary tasks?

A new transportation system must be acknowledged by other road users and accepted. A HC vehicle must be known by other road users to avoid that the public opinion feels threatened by vehicles in which the driver is showily distracted, all while overtaking, turning or changing lanes.

Research Question: Does the HC vehicle perform maneuvers too conservatively or too aggressively, thus fostering a feeling of aversion in the other road users or in the public opinion?

A HC vehicle that doesn't overtake and passively occupy a lane can make the overtaking maneuver more difficult for the following vehicles and frustrate their drivers. On the other hand, performing lane changing and overtaking too aggressively can increase the feeling of threat that an HC vehicle can cause in the other road users, which can see a vehicle intruding their lane with low gap values while the driver is playing with a mobile phone, for example. Another subject that should be considered is the capability of the HC vehicle to interpret other vehicle's intentions efficiently enough to not cause sudden accelerations, braking or evasive maneuvers in conflictual points such as ramps.

Research Question: Is the relationship between the driver and the automated system perceived correctly, with the right level of trust and a clear mental representation of what the system can and can't do?

- *How does the HC vehicle's driver perceive the take-over transitions? How readily does he react to system warning and indications?*

As summarized in chapter 2, it is important that the warning delivered to the driver communicate the right urgency. This urgency shouldn't be lowered to encounter the driver preferences (which could hinder the safety of the transition maneuvers) but shouldn't be unnecessarily high either. In fact, if the driver perceives each transition in control as dangerous he or she could choose to not engage the system anymore.

- *Is the level of trust in the automated system correctly related to the actual situation and system capabilities?*

It is important that the driver doesn't overestimate the system capabilities and knows exactly which functions are accomplished by the automation (and when). Accomplishing this not only guarantees safety but can also improve the acceptance from the driver. Having a clear and precise knowledge of what the system does, in fact, makes the acquaintance with the automation easier (a calibrated trust, as defined in [39], means that the user's trust matches the automation capabilities).

- *Does the driver accept changing in the ACC parameters triggered by external sources or related to the surrounding traffic conditions?*

As summarized in chapter 2, positive impacts on Traffic Efficiency can be obtained if the kept time gaps can be tuned accordingly to the surrounding traffic conditions. It should be assessed, though, if the driver of the HC vehicle accepts these external interferences on the HC vehicle driving regime.

- *Does the driver set the ACC time gaps similar to the ones he would keep in manual driving?*

In general, it should also be assessed what kind of headway the drivers prefer when activating the automated function and beyond what value they prefer to resume control.

- *Does the driver prefer a more aggressive motion planning algorithm or a more conservative one?*

It is important to understand to what extent the drivers accept more conservative driving styles and increased travel times and in what kind of circumstances they choose to set more aggressive driving styles in order to reach their destination, instead. It is important to note that an increased travel time can also be favoured if the more conservative driving regime reduces the motion sickness and makes the secondary task more enjoyable. Moreover, the driver's perception of the single maneuvers (lane changing, overtaking, yielding) should be assessed to better foresee what kind of HC vehicles will be sold and will drive on public roads.

- *How does the driver perceive warnings and information delivered through auditory, haptic or visual support? Does he accept also general information or prefer just indications about imminent take-over maneuvers and mandatory indications?*

How the driver perceives the mean of transmission influences how he will respond to the delivered warning and its perception of the full trip (how much comfortable and safe it is, for example). Besides, the number of delivered information shouldn't be overwhelming and cause, in the driver, a feeling of aversion towards the HMI and its warnings that could lead to misuse (as defined in [39], namely when the driver fully comprehend the alert but attempts to ignore it). It should be noted that different kind of information can be delivered through different means and with different urgency. For example, lane changing and overtaking maneuvers can be displayed on the HMI to ensure mode awareness [2] but not be signalled through auditory or haptic inputs while more urgent information can be delivered in a more intrusive way, instead.

Assessment instrument

To assess Overall and User Acceptance, the most efficient tools are Surveys presented after field tests and large-scale demonstrations. Moreover, for the User Acceptance, data from inside cameras and Can Bus could be employed to determine when the driver disengages the system

to re-engage the driving task. The use of wearable garments should be evaluated to assess the psychophysical state of the driver, especially during take-over maneuvers.

4. Jointed impacts of Highway Chauffeur and C-ITS

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

- Traffic Efficiency
- Safety
- Environment
- User Acceptance

Specifically, how both the systems interact in order to maximize their benefits will be analysed. The scenarios considered will concern an HC vehicle equipped with, at least, ACC, Lane Keeping Assist, Lane Change Assist, an emergency brake system, and the perception system described in the precedent paragraphs. Also, the possibility to receive all the cooperative messages V2V and V2I (by the means of the messages standardized in the ETSI documents) is considered. For the C-ITS services, the implementation scenarios will be the ones determined during the European activities of C-Roads, referring to the defined use cases. These guidelines will be drafted only for the ones among the use cases judged relevant when referred to the Highway Chauffeur driving in the short and medium term. This means that, for example, the service group “Functional Description of Traffic Light Maneuvers & Road and Lane Topology” is not going to be studied in the present Ex Ante because not judged relevant for an HC vehicle (on the basis of the Chapter 2 bibliographical review). The Highway Chauffeur system, in fact, is confined to highway scenarios where the traffic lights could be present only for ramp-metering strategies and in limited number. Besides, the definition of some services is still being developed in the C-Roads activities and is seen as premature to draft a methodological approach to assess the impact for scenarios still changeable. That is the case of use cases and services like Emergency Electronic Brake Light, Shockwave Damping or the Emergency Vehicle Approaching. Also for the Road Works Warning service, for example, many use cases have still to be clearly defined and is, then, judged as overhasty to define research and sub-research questions for them.

This chapter, therefore, focuses on the services and use cases judged relevant in their jointed implementation with the Highway Chauffeur among the Day 1 ones that are being defined by the C-Roads Platform. This selection has been conducted on the basis of the extensive bibliographical review and with the following objective: define an evaluation methodology able

to guide evaluators in designing field tests and modeling works in the next future to assess the impact of two innovative and still evolving transport systems (Highway Chauffeur and Cooperative ITS). This work, then, isn't aimed to define all the possible joint impacts and surely can be expanded to consider the remaining C-ITS Day 1 services and the services of cooperative mobility foreseen for broader time horizons (Day 1.5 and Day 2, for example).

For each one of the services judged relevant in function of what stated above, the most likely scenarios will be considered and the inputs and outputs required to assess the impacts will be highlighted. The followed approach is based on "Research and Sub-Research Questions" and follows FESTA Handbook (FOT-Net 2017):

- Research Question: When the C-ITS service allows the Highway Chauffeur to overcome an event that could possibly make it leave its ODD is described, analysing how to quantify the number of added kilometres driven by the automated system. Moreover, the effect of the C-ITS service on the smoothness and safety of the take-over transition and on the efficiency of the carried out maneuvers is also investigated. Besides, the increased efficiency of an HC system is expected to impact on the surrounding traffic flow and, therefore, on the service outputs and on the benefits obtained through the C-ITS.
- Examples of Sub Research Questions could be "Does the C-ITS service allow the HC to keep driving without re-engaging the driver in the driving loop?" or "The HC vehicle changes its behaviour in response to a C-ITS service? Does it overcome the events or issue a take-over maneuver in advance thanks to the received information?" The changes of the parameters that characterise the service functioning/HC driving are investigated for each relevant scenario, possible data requirements are mentioned.
- Suggested methods and tools to quantify the impact of the jointed implementation on the impact areas listed above are mentioned, referring to the bibliographical review in chapter 2 and to the C-Roads documents describing the C-ITS services. Parameters possibly needed as output and how to measure them will be mentioned.
- Overall future estimated impacts, shortly presented only when an increased number of HC vehicles among the traffic flow entails strong and evident impacts in their jointed implementation with C-ITS services. Only the Day 1 services and only the present level of automation are considered.

This work aims to tackle a need arising because both the Highway Chauffeur system and C-ITS services are not yet implemented on public roads (with some exceptions about C-ITS projects

and corridors), it is not possible, then, to obtain numerical results bound to their jointed implementation. Also, about this subject, a bibliographical review that could be used to assess the impacts is still scarce. Therefore, in this chapter, a similar approach to the one followed for chapter 3 will be employed, referring to the separate bibliographies and states of the art about Highway Chauffeur and Cooperative Mobility.

How to investigate in depth each scenario, which data requirements meet and output indicators measure is left to choose for the evaluator as function of the test specificities and, also of the regional features. Also, it should be noted that these evaluation guidelines have been designed to be applicable in general scenarios and are not referred to specific field tests or modeling works carried out in the C-Roads Italy activities (during which there will certainly be field tests but not every subject listed in the following paragraph will be evaluated). Finally, it should be highlighted that, traditionally, an Ex Ante evaluations doesn't cover the assessment instrument, data requirements or the indicators that could be obtained to study the impacts of an innovative system but simply draws the expected impacts from the available bibliography, identifies the state of the art and lays the foundation for the design of the Ex Post evaluation (that will be carried out in the next years as another one of the activities within C-Roads Italy). The present work in the chapters 3 and 4 goes a little beyond a traditional Ex Ante and draws a first methodology on the basis of which the future evaluation works can be designed, defining the relevant parameters and the hypotheses that could be employed to quantify the impacts of the implementation, on public roads, of both the Highway Chauffeur system and the majority of the Day 1 C-ITS services.

Please note that the modal form "should / should not" is employed in this paragraph to indicate recommendations and suggestions, therefore no mandatory value should be given to what is stated.

"Cooperative Intelligent Transport Systems (C-ITS) connect vehicles with each other and with the road infrastructure, allowing road users and traffic managers to share information and use it to coordinate actions. This cooperative element is expected to bring significant benefits for road safety, traffic efficiency and driving comfort. It is considered important to increase the safety of future automated vehicles and their integration in the overall transport system, [...]. The vision is that cooperative ITS, connectivity and automation are complementary technologies and shall reinforce each other and converge over time." [19]

4.1. Road Works Warning

Service description

On the basis of what is stated in [69], the following considerations can be taken. This service is intended to provide warnings to road users approaching short-term or long term road works, mobile or static. The Use Cases considered in their joint implementation with the Highway Chauffeur system are:

- Closure of part of a lane, whole lane or several lanes
- Alert planned road works – mobile

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

It should be noted that for the Use Cases defined above it seems useful to evaluate both the driver's behavioural response and the automated system's one (that can react without involving the human driver if an appropriate function is implemented in its control algorithm).

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

The drivers know in advance, by the means of the C-ITS service, of a lane closure due to roadworks. This way they can change lane earlier and in a smoother way, making the traffic flow readier to approach the critical stretch. On the basis of Chapter 2 (Highway Chauffeur – Bibliographical Review), the knowledge about the situation on the road ahead can be employed by the Highway Chauffeur system both to expand its ODD and become, for example, able to pass a work zone and to warn the driver in advance about the imminent take-over request (this way the shift in control can be performed safely and in a more efficient way).

4.1.1.1. Traffic Efficiency

Research Question: Does the information forwarded in advance make the HC vehicle able to pass the work zone without exiting its ODD?

A roadworks constitutes a critical stretch on the road branch, along which vehicles travel with an increased density and reduced speed values. Congestion, then, arises faster and propagates upstream easier. In such a critical scenario an automated vehicle can both worsen or ease the traffic condition, depending on the ACC parameters set (that can be modified accordingly to the roadworks situation, if such a feature is implemented into the system). If the time gaps are the

ones set by the driver according only to their comfort levels, a decreased capacity is obtained because more space is occupied on the road branch. If the Highway Chauffeur system is designed in a way that, when informed about a bottleneck congestion, the ACC parameters are adjusted accordingly, a beneficial effect is experienced by the overall traffic flow. Moreover, allowing the HC vehicle to maintain its automated driving regime avoids negative impacts caused by the take-over maneuver and guarantees a longitudinal control more efficient than the human one (as mentioned in chapter 2, if the automated system is engaged the Traffic Jam Chauffeur function can be exploited). It should be also noted that a degradation cascade strategy can be adopted by the system that can leave the lateral control to the human driver while keeping the longitudinal control for itself.

Another effect can be obtained if the HC vehicle receives the information about the roadworks in advance: a lane changing maneuver can be performed as soon as the right gap is identified, resulting in a more efficient driving behaviour and lower impacts on the traffic upstream. Besides, if the HC vehicle can change lane in advance, the risk of it being stuck just at the entrance of the roadworks because a more conservative algorithm isn't able to change lane without the intervention of the driver is lower (a similar scenario would involve unacceptable time losses). Notable information that can be broadcasted by the service, besides the presence of the roadworks, can be the speed limit of each affected section or geospatial information and possible traces approaching the work zone together with the eventHistory element, both contained in the DENM data [101]. Depending on the information broadcasted by the C-ITS, the Highway Chauffeur system can evaluate more precisely and in advance if the roadworks ahead falls into its own ODD or if the traces allow it to enter the roadworks and keep driving while in automated mode. The more detailed the available itinerary, the more adverse weather conditions can be faced, for example. Another issue that can be overcome could be the inadequacy of the lane markings that confine the roadworks, sensors' failure can be confronted too, thanks to an achieved redundancy with the received information.

- *Does the information forwarded in advance contains elements that make the Highway Chauffeur system able to pass the roadworks without having to fall-back on the human driver?*

Roadworks that cause the closure of one or more lanes can alter the whole road topology and the lane markings used by the HC vehicle to drive autonomously (through functions such as the lane keeping assist). Besides, the work zone is often signalled by the means of road cones which can be difficult to perceive through the equipped sensors. Therefore, every information broadcasted by the C-ITS service about the occupied lanes and

possibly feasible waypoints can support the HC vehicle in its driving task, allowing it to pose itself on the right lane in time or to approach the roadworks with the right speed and giving additional information, achieving redundancy with what is perceived by the on-board sensors.

- *Is the HC vehicle's lane changing maneuver smoother thanks to the received information?*

Knowing in advance about the work zone triggers earlier, in the HC vehicle, the necessary lane changing maneuver. The information can foster also the efficiency of the lane change in human-driven vehicles, for an HC vehicle an added value arises, though, because the motion planning algorithm can tune the aggressiveness of the needed lane changing maneuver accordingly and prevent a too conservative approach from halting the HC vehicle just before the working zone. It should be noted that, upon discovering about the roadworks, the HC vehicle can reduce the kept time gaps and the space between itself and the preceding vehicle. This should prevent other vehicles from cutting in in front the HC vehicle, exploiting the incremented gaps set by the human drivers (cut-ins impose braking on the following vehicles, especially when performed with reduced distances).

- *Does the HC vehicle adapt its speed earlier and in a more efficient way thanks to the forwarded information? Is its speed more homogeneous?*

Knowing in advance about the needed deceleration allows the ACC function to adapt the desired speed in a way that smooth deceleration values and no harsh braking are performed by the HC vehicle (therefore achieving a more efficient speed adaptation performed by the automation that could also impact the following vehicles). It should be noted that a speed adaptation performed by the automation on the basis of a continuously updated information is expected to be more efficient than the one performed by a human driver. Besides, knowing continuously about the dynamic speed limit that should be maintained across the roadwork can guarantee a more efficient and homogeneous driving in its longitudinal control.

- *Does leaving the Traffic Jam Chauffeur turned-on help easing the bottleneck congestion? Do increased time gaps worsen the bottleneck congestion, instead?*

It should be evaluated if leaving the longitudinal control active across the work zone and the bottleneck congestion foster the recovering to the regular traffic flow when the Traffic

Jam Chauffeur function is engaged. On the other hand, when the flow is not completely congested and the driving regime is different from the Stop&Go one, increased time gaps due to conservative algorithms can worsen the overall traffic throughput. The information broadcasted by the service can trigger a tuning of these value in the algorithm, favouring more efficient driving strategies.

Assessment instrument

To assess the jointed impacts, both field tests and modeling works can be employed. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. Examples of this kind of specifications can be found in the dedicated C-Roads documents [69]. Besides, during field tests, the lateral control function must be validated in its safety-related aspects before the actual on-road experiment, with particular attention to the fall-back solutions and to the magnitude of a possible system failure. Moreover, the ODD should be clearly defined. The baseline scenario should consider both HC vehicles unequipped for the cooperative message reception and manually driven vehicles (both equipped and unequipped), another scenario that should be compared is the one that considers the possibility of suggested time gaps values to the HC vehicle provided or triggered by the C-ITS to enhance the overall Traffic Efficiency (versus the scenario in which the time gaps are the one pre-set in the ACC system).

Research Question: Does the information forwarded in advance allow an earlier take-over request, allowing the driver to re-engage the driving task and reach the work zone with complete situational awareness?

As mentioned in chapter 2, a take-over request delivered to the driver earlier and with less urgency should foster a more efficient maneuver that involves smoother braking and fewer swerving of the HC vehicle. This, in turn, should decrease the impact on the surrounding traffic flow and on the overall Traffic Efficiency. It should be noted that both sudden braking and lane changing maneuvers impose perturbations on the following vehicles and upstream the traffic flow. An earlier take-over request, triggered thanks to the C-ITS, increases the time available for the driver to re-acquire a proper level of situational awareness, essential for an efficient driving through the roadworks.

- *Does an earlier take-over request diminish the number of sudden braking performed by the human driver?*

As mentioned in chapter 2, an urgent take-over request can induce sudden responses in the human driver. If the Highway Chauffeur system receives in advance the information about the work zone, the take-over request can be issued with less urgent tones. This should result in smoother decelerations, appropriate to lead the HC vehicle to the right speed value, and therefore reduced or null perturbations upstream the traffic flow.

- *Does an earlier take-over request help the human driver perform a more efficient lane changing maneuver, preventing its vehicle from being stuck just before the work zone?*

Having more time to re-engage the driving task and start searching for sufficient gaps on the other lane should help the human driver in performing more efficient lane changing maneuver and prevent sudden lane changes with reduced available gaps (and the related impacts on the upstream traffic flow).

- *Do an earlier take-over request and the information delivered by the C-ITS improve the situational awareness of the human driver and, consequently, the efficiency of his driving?*

In general, if the driver has a clear mental representation of the driving task, he should be able to perform it better, interacting with the surrounding road users and accomplishing maneuvers as efficiently as he can. An earlier take-over request and an increased number of information delivered through the HMI should favour this scenario.

- *Does the C-ITS make a partial degradation in the automation level possible or easier? Does the driver resume lateral control more efficiently, while leaving the longitudinal control to the Highway Chauffeur system?*

Driver's performance while re-engaging only part of the driving task could benefit from an earlier notification and lower urgency in the same way it happens for the whole take-over transition. The impact on this kind of transition should be evaluated, it should also be noted that, for the same roadworks, different requests can be issued by the Highway Chauffeur system, depending on the lane marking conditions, light and weather conditions and other ODD-related parameters. Therefore, the driver doesn't exactly know if the system will ask for its intervention or what function he will need to re-engage.

Allowing the driver to maintain only lateral control and leaving the longitudinal control to the automation should increase the number of roadworks travelled through by ACC-controlled vehicles or vehicles with the Traffic Jam Chauffeur function activated. Thus, an increased level of efficiency should be achieved for the overall traffic through the roadworks.

Assessment instrument

To assess the jointed impacts, both field tests and modeling works can be employed. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. Examples of this kind of specifications can be found in the dedicated C-Roads documents [69]. Also, during field tests, the lateral control function must be validated in its safety-related aspects before the actual on-road experiment, with particular attention to the fall-back solutions and to the magnitude of the possible consequences of a system failure. Besides, the take-over maneuver must be evaluated before the on-road test in order to assess safe transition times. Moreover, the ODD should be clearly defined. The baseline scenario should consider HC vehicles unequipped for the cooperative message reception, other scenarios that should be compared are the one that consider different warning strategies to re-engage the human driver in the driving loop and the correct set of information that should be presented to maximize his capability to re-obtain an acceptable level of situational awareness.

4.1.1.2. Safety

Research Question: Do the information forwarded by the C-ITS support the Highway Chauffeur system in its driving task across the roadworks? Does the C-ITS prevent last minute ODD violations?

If the C-ITS delivers not only information about the presence of the work zone but also about the modified road topology, possible traces and other details that can support the perceiving system and/or offer redundancy (especially when the environmental conditions are adverse), the number of roadworks exiting the intended ODD should lower. An "extension" of the system ODD means an increased number of kilometres driven by the automated system which, on the basis of what is reported in Chapter 2, can be considered safer than the ones driven by a human. Moreover, the broadcasted speed value defined for each section supports the HC vehicle in the

longitudinal control task, allowing it to adapt the target speed earlier and perform smoother and safer decelerations.

- *Is the HC vehicle's lane changing maneuver smoother thanks to the received information?*

As mentioned in the previous paragraphs, knowing in advance about the need to perform a lane changing maneuver increases the number of disposable gaps on the other lane before arriving to the lane closure and allows the HC vehicle to perform the maneuver exploiting the wider ones. This should result in increased TTC times between the HC vehicle and the other ones on the other lane.

- *Does the HC vehicle adapt its speed while approaching the work zone in a smoother and safer way?*

Knowing in advance and continuously about the work zone and the suggested speed limit for each one of the preceding sections should allow the HC vehicle to adapt its driving speed in advance, avoiding abrupt decelerations and giving redundancy to the information derived from the signalling on the road (that must be perceived by the sensors).

- *Does the number pre-crash scenarios lower thanks to the information granted by the C-ITS?*

The main issue with the safety assessment could be the unsuitableness of field tests for the comparison of the number of accidents between scenarios (hopefully, during a field test rather limited both in time and space, the number of accidents should be insufficient). Thus, in order to assess the impact of the redundancy achieved through the C-ITS, the number of pre-crash scenarios should be employed. The additional information provided by the C-ITS message should lead to fewer scenarios in which critical values of TTC and/or Brake Threat Number or analogous metrics are reached.

- *Does the information delivered by the C-ITS widen the system ODD, avoiding take-over maneuvers?*

If additional information is broadcasted (traces and eventHistory, for example), able to support the HC vehicle in its driving task, it could become possible to avoid take-over maneuvers even if the work zone delimitation is not well defined in each point across the roadworks or if the environmental conditions are not the most suitable for environmental perception. Additionally, an increased number of information can offer redundancy to the Highway Chauffeur system, serving as fall-back if suddenly a lane mark is no longer

detected. Allowing the HC vehicle to keep the automated driving regime not only nullify the risks related to the take-over maneuver but can guarantee protection against rear-end collisions (thanks to the Traffic Jam Chauffeur system remaining engaged).

Research Question: With the information forwarded in advance or in a more intrusive way, are the take-over maneuvers carried out in a safer and less sudden way?

Knowing about the lane closure in advance can trigger earlier the take-over request issued by the HC system (if for example adverse weather conditions are detected or if the information broadcasted by the service aren't complete enough to guarantee the possibility to remain in the intended ODD). Having more time at disposal lowers the urgency of the request and allows the driver to re-engage the driver task smoothly and to regain full situational awareness. Also, the speed can be adapted avoiding harsh braking.

- *Is the take-over maneuver carried out in a smoother way? Does the driver re-gain control avoiding sudden maneuvers?*

Receiving information about the lane closure allows the driver to re-engage the driving task safely and knowing about the suggested speed limit should lead to smoother decelerations before reaching the working zone, reducing the rear-end collision risk and enhancing the safety of the roadworks. It should be noted that even if the HC vehicle perceives the signalling about the roadworks ahead, a driver responding to the warning can brake more abruptly also when the space left before the working zone is more than enough, especially when inexperienced drivers are considered.

- *Does the driver achieve an acceptable level of situational awareness before performing the lane changing maneuver?*

Being taken back into the driving loop earlier grants to the driver the capability to regain complete situational awareness before having to perform any maneuver. Guaranteeing to the driver the time to assess the cause of the warning, the remaining distance and the state of the surrounding traffic should favour an increased safety in its driving behaviour, especially when performing the needed lane changing maneuver (a driver in a hurry can settle for reduced gaps on the other lane).

Assessment instrument

The Safety evaluation should be done mainly through modeling or bibliographical review, but can't be complete without field tests able to validate the designed system and how it interacts with the surrounding traffic. The capability of the HC system in responding to unforeseen scenarios related to roadworks (such as narrow lanes, ruined lane markings, signalling through cones, etc.) should be assessed with a huge number of kilometres driven. In designing these tests on the road, guidelines like the ones drawn from the NHTSA can be considered, in [45], for example, the main safety-related design aspects are listed to be considered when deploying automated systems on public roadways. Besides, field tests or virtual testbeds can be employed to assess behavioural inputs to design appropriate car following models and safety critical scenarios in modeling works. Other behavioural subjects that can be investigated, even with more local field tests, concern the control transition between the HC system and the human driver, take-over time and the relationship between the two authorities on-board (the human driver and the HC system). When designing field tests involving roadworks, the right set of information to broadcast to the driver to maximize its capability to re-take situational awareness should be investigated (e.g. distance from the roadworks, number of closed lanes, dynamic speed limits, etc.). Besides, pre-crash scenarios and critical situations typical of the roadworks scenario can be evaluated through field tests or modeling works and employed to evaluate the overall safety of the system. The shift in control should be evaluate prior to field tests by the means of digital testbeds, to guarantee a safe transition time in each scenario. The baseline scenario should consider HC vehicles unequipped for the cooperative message reception and manually driven vehicles (both equipped and unequipped), another scenario that should be compared is the one that considers the possible degradation of the automated function (with the human driver resuming the lateral control while the longitudinal control function is still engaged). In general, no roadworks should be encountered twice by the drivers, to avoid results influenced by any previous acquaintance with the situation. The data collected should also be relevant to investigate any incidents that may occur (achievable through Event Data Recorders) and the pre-crash scenarios detected (on the basis of the safety-related metrics) should be recorded. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. Examples of this kind of specifications can be found in the dedicated C-Roads documents [69].

4.1.1.3. Environment

Research Question: Does the information granted in advance promote a more energy efficient driving regime, both if the control remains to the automation or shift towards the human driver?

The same scenario described in the Traffic Efficiency research question (4.1.1.1) is applicable for the Environment impact area. An earlier notification (possibly including information about the road topology ahead) leads to a widening of the systems ODD, allowing an increased number of HC vehicle to pass through the work zone without issuing a take-over request. This hypothesis implies that a fair share of vehicles among the traffic flow keep driving in a more energy efficient regime (granted by the automation), possibly influencing also the surrounding traffic flow. A more efficient driving regime decreases the number of sudden maneuvers and resulting braking in the following vehicles, thus enhancing environmental gains. A more efficient speed regime can be obtained, for example, when a dynamic speed limit is suggested before the roadworks.

- *Does the service allow a greater number of HC vehicles to keep driving without issuing a take-over request to the human driver?*

Depending on the information broadcasted by the C-ITS, the Highway Chauffeur system can evaluate more precisely and in advance if the roadworks ahead falls into its own ODD. This way two main beneficial scenarios are reached, the number of take-over maneuvers is lowered (thus limiting the number of sudden braking and flawed maneuvers) and a more efficient driving regime is preserved (the automated one).

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

Granting more time to an HC vehicle to perform the lane changing maneuver can prevent more conservative algorithm from being stuck on the wrong lane, once the roadworks section is reached, or reduce the need of performing lane changing maneuvers with reduced gaps on the other lanes. Avoiding both these scenarios should foster a more energy efficient driving regime both for the HC vehicle and for the surrounding vehicles affected by the maneuvers performed by the automated vehicle.

- *Does leaving the Traffic Jam Chauffeur turned-on help easing the bottleneck congestion? Do increased time gaps worsen the bottleneck congestion, instead?*

As stated in 4.1.1.1, it should be evaluated if leaving the longitudinal control active across the work zone and the bottleneck congestion actually fosters the recovering to the regular traffic flow when the Traffic Jam Chauffeur function is engaged. On the other hand, when the flow is not completely congested and the driving regime is different from the Stop&Go one, increased time gaps due to conservative algorithms can worsen the overall traffic throughput. The information broadcasted by the service can trigger a tuning of these value in the algorithm in order to delay or avoid congestion and, thus, fostering a more energy efficient driving regime for the overall traffic flow.

Assessment instrument

Assessing the environmental impacts on the traffic flow during field tests should be accomplished by changing both the percentage of HC vehicles in the traffic flow and the ACC-related parameters (as explained in Chapter 2, in fact, the effect of ACC-equipped vehicles among the traffic flow depends on the time gaps set). The potential stabilizing effect of HC vehicles (granted by an optimal longitudinal and lateral control achieved by the means of the automation) should be evaluated for different levels of market penetration, similar considerations can be made for the Traffic Jam Chauffeur function, designed as a comfort function but potentially able to ease congestion if a fair share of equipped vehicles is queued. It should be also noted that an evaluation can result in negligible impacts of a Highway Chauffeur system on the Environment, if for example the ACC is implemented only as a comfort function or the market penetration is too low (the Highway Chauffeur isn't conceived to gain environmental benefits). Field tests can be designed to obtain the behavioural inputs that a model can employ to assess fuel consumption and, then, environmental impacts. The baseline scenario should consider HC vehicles unequipped for the cooperative message reception and manually driven vehicles (both equipped and unequipped), other scenarios that could be compared considers different time gaps and, potentially, adaptation of these value to apply traffic control strategies similar to the ones in [32,57]. In general, no roadworks should be encountered twice by the drivers, to avoid results influenced by any previous acquaintance with the situation. Besides, different level of market penetration should be evaluated; in [20], for example, the results of the carried-out simulations showed that for a presence of automated vehicles equal to 50%, the interactions between automated vehicles grow to relevant levels and foster a decrease in relative velocities (which, in turn, entails higher environmental benefits). The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication

ranges, the means of broadcasting and the information transmitted. Examples of this kind of specifications can be found in the dedicated C-Roads documents [69].

4.1.1.4. User Acceptance

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

Re-engaging the driving task after a moderately long time involved in a secondary task can potentially induce a feeling of urgency and/or danger in the human driver, thus worsening the whole driving experience. If the C-ITS service is received earlier and delivers a more complete set of information, when compared to signals on the side of the road, the driver can reacquire situational awareness easily and approach the roadworks with confidence. It should be noted that these considerations depend also on when and how the message is displayed by the system according to the OEMs design.

Assessment instrument

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

Survey's Outputs

The following indicators should be collected after surveys:

- Situation awareness
- Knowledge about the Highway Chauffeur system and its capabilities
- Problem perception related to the approached roadworks
- Perceived threats for the driver himself or for the workers on the road

4.1.2. Alert planned road works – mobile

The driver knows in advance about the neutralization of part of a lane or a lane closure due to mobile work sites, the main objective achievable through this Use Case is an increased safety for mobile roadworks that are usually “lighter” in terms of protection and signalling. The decreased protection and, somehow, visibility of the roadworks are the main issue for an HC vehicle, compared to the scenarios defined in 4.1.1., so the main gain that the Highway Chauffeur system can obtain by this Use Case concerns an increased “awareness” of the

system about the mobile roadworks and a redundancy to what is perceived through the perceiving system. Other desired behaviours listed in the Use Case description [69] are an adaptation of the kept speed before reaching the roadworks and a change of lane more efficient if needed and possible.

Because the scenarios are pretty similar to the ones defined in 4.1.1, all the considerations presented in that paragraph can be considered valid for this use case too.

4.2. In Vehicle Signage

Service description

On the basis of what is stated in [70], the following considerations can be taken. This service is intended to provide information to the road users about road signs approached during the driving, both mandatory and advisory. The signs broadcasted to the vehicle can be the ones indicated on physical road signs along the road or concern additional virtual information (such as the information delivered through VMS or free text) and can target specific vehicle types.

The use cases considered in their joint implementation with the Highway Chauffeur system are:

- Dynamic Speed Limit Information
- Embedded VMS “free text”
- Other signage information

The benefit that the service alone is meant to achieve is mainly an increased safety bound to a higher situational awareness, besides improvements in Traffic Efficiency and Environment could also be obtained. It should be noted that, for the Use Cases defined above, it seems useful to evaluate both the driver’s behavioural response and the automated system’s one (that can react without involving the human driver if such a function is implemented in its control algorithm).

4.2.1. Dynamic Speed Limit Information

The driver receives the speed limit notification concerning a suggested value, lower than the one signaled on the road, issued by the Traffic Control Center or by a Service Provider. On the basis of Chapter 2 (Highway Chauffeur – Bibliographical Review), the knowledge about the suggested speed limit can be employed by the HC vehicle to assume a more efficient driving

behaviour, both from its point of view (possibly avoiding the congestion ahead and assuming a driving regime more energy efficient) and for the overall traffic flow (delaying the arrival of the HC vehicles to the congested section should ease the severity of the congestion). Besides, receiving a continuously updated value allows the HC vehicle to adapt its driving in a smoother way compared to the scenario in which the same information is delivered through VMS.

4.2.1.1. Traffic Efficiency

Research Question: Does the information forwarded to the HC vehicle delay its arrival to the congested section (e.g. roadworks, incidents, traffic jams), thus fostering an earlier return to the decongested state?

Providing with the suggested speed limit information a sufficient number of HC vehicles upstream the congested section should ease the weight on the congested section itself, limiting the number of vehicles approaching it. The benefits are rather similar to the ones achievable by the C-ITS alone, informing traditional vehicles about the suggested speed limit. However, it should be noted that an HC vehicle can keep the speed value more precisely than the average human driver and, if the control algorithm is designed accordingly, should always adapt its behaviour (while some human driver can choose to ignore the suggestion). As stated, for example, in [37] between the optimal driver behaviour and the worst one there is up to a 20% difference, on the efficiency side. Therefore, it should be evaluated what percentages of HC vehicles in the traffic flow actually enhance Traffic Efficiency.

➤ Is the HC vehicle's speed more compliant with the suggested speed limit?

While driving in its ODD, the HC vehicle can adapt its speed accordingly to the received information without bothering the human driver. If that is the case, the HC vehicle should be able to adapt its speed precisely and react promptly to the possible updates. The behavior of the HC vehicle that receives a dynamic speed limit is a choice of the OEMs, though, so all the possible designed solutions could be evaluated (an HC vehicle could ignore the suggestion and reach as soon as possible the congestion, being able to exploit the Traffic Jam Chauffeur function).

➤ How do the instant speed fluctuations change?

As for the human driven vehicles, receiving the information continuously updated on board allows the HC vehicle to adapt its speed value smoothly (while receiving the speed limit only through VMS could cause more abrupt braking or accelerations). Exploiting the C-ITS information, the HC vehicle should be able to adapt its driving speed in a smoother

way, impacting less on the surrounding traffic flow and limiting the generation and the propagation of shockwaves.

- *Does delaying the arrival of HC vehicle to the congested section actually improve the overall traffic efficiency?*

It should be assessed if it is more beneficial for the congested traffic flow having a fair share of HC vehicle driving upstream or driving among the congestion. In the first case a lower number of vehicles reaches the congestion front that should fade earlier, in the second case the increased efficiency of the Traffic Jam Chauffeur function is exploited, though, obtaining another relieving effect on the congestion. Therefore, depending on the operational parameters of the longitudinal control law and on the market penetration of HC vehicles, the most efficient approach should be defined. Moreover, having HC vehicles driving slower upstream the congested front should impose lower speed values also to the traditionally driven vehicles that would be forced to overtake to maintain their desired speed value (likely higher than the suggested one).

- *How does having ACC-equipped vehicles upstream the queue impact on the congestion recovery? Is some sort of time gap adaptation designed in their algorithms?*

If the ACC-equipped vehicles are designed to drive in the most overall efficient way when approaching congestion, they should improve Traffic Efficiency. The percentage of these vehicles upstream or along the congested section necessary for the benefit to arise should be evaluated, besides the parameters of the ACC able to foster this increased efficiency should be assessed together with the possible control strategies that the algorithm can adopt to react to the surrounding traffic situation (e.g. the ones showed in [32]).

Assessment instrument

To assess the jointed impacts, both field tests and modeling works can be employed. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. Examples of this kind of specifications can be found in the dedicated C-Roads documents [70]. The baseline scenario should consider both HC vehicles unequipped for the cooperative message reception and manually driven vehicles, moreover, different behaviours of the Highway Chauffeur system in relation to the suggested speed limit should be

evaluated in their compliance. The potential stabilizing effect of HC vehicles (granted by an optimal longitudinal and lateral control achieved by the means of the automation) should be evaluated for different levels of market penetration, similar considerations can be made for the Traffic Jam Chauffeur function, designed as a comfort function but potentially able to ease congestion if a fair share of equipped vehicles is queued.

4.2.1.2. Safety

Research question: Does the broadcasted suggested speed limit prevent the HC vehicle from approaching a congested section with an unsafe speed value?

Avoiding speeding and potentially reaching the end of the queue with an already decreased speed could lower the number of rear-end collision scenarios. The actual impact of the Use Case on safety should be evaluated keeping in mind that the HC vehicle should be generally equipped at least with the Autonomous Emergency Braking that should prevent rear-end collisions or lower their severity. Overall, the safety impacts of this Use Case are pretty much similar to the ones achievable by a human driven vehicle, if not lower.

4.2.1.3. Environment

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

If the HC vehicle reacts to the information adapting its driving speed it should arrive later to the congested section, possibly when the congestion has already faded away. The information granted by the C-ITS service should increase the number of kilometres driven with a constant velocity and decrease the portion of the route travelled in a regime of Stop&Go. Thus, a more energy efficient driving regime should be achieved, lowering the fuel consumption of the HC vehicle. These benefits are rather similar to the ones achievable by the human driven vehicles receiving the same information.

➤ How do the instant speed fluctuations change?

Having the information broadcasted in advance and continuously to the vehicle should lead to a more homogeneous driving style, thus lowering fuel consumption and emissions.

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

Lowering the driving speed to the value suggested by the C-ITS should allow the HC vehicle to increase the amount of time in which no congestion is encountered and the driving speed can remain rather homogeneous. Even if the vehicle reaches the congestion front it must face a Stop&Go regime for less time, thus achieving a more energy efficient driving regime.

- *How does having ACC-equipped vehicles upstream the queue impact on the congestion recovery? Is some sort of time gap adaptation designed in their algorithms?*

If the ACC-equipped vehicles are designed to drive in the most overall efficient way when approaching congestion, they should improve Traffic Efficiency and, therefore, promote a more energy efficient driving regime for the traffic flow. The percentage of these vehicles upstream or along the congested section necessary for the benefit to arise should be evaluated, besides the parameters of the ACC able to foster this increased efficiency should be assessed together with the possible control strategies that the algorithm can adopt to react to the surrounding traffic situation (e.g. the ones showed in [32])

Assessment instrument

Assess the environmental impacts on the traffic flow during field tests should be accomplished changing both the percentage of HC vehicles in the traffic flow and the ACC-related parameters (as explained in Chapter 2, in fact, the effect of ACC-equipped among the traffic flow depends on the time gaps set). The potential stabilizing effect of HC vehicles (granted by an optimal longitudinal and lateral control achieved by the means of the automation) should be evaluated for different levels of market penetration, similar considerations can be made for the Traffic Jam Chauffeur function, designed as a comfort function but potentially able to ease congestion if a fair share of equipped vehicles is queued. It should be also noted that an evaluation can result in negligible impacts of a Highway Chauffeur system on the Environment, if for example the ACC is implemented only as a comfort function or the market penetration is too low, the Highway

Chauffeur isn't designed to gain environmental benefits. The baseline scenario should consider HC vehicles unequipped for the cooperative message reception and human driven vehicles (both equipped and unequipped), other scenarios that could be compared considers different time gaps and, potentially, adaptation of these value to apply traffic control strategies similar to the ones in [32,57]. Field tests can be designed to obtain the behavioural inputs that a model can employ to assess fuel consumption and, then, environmental impacts. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. Examples of this kind of specifications can be found in the dedicated C-Roads documents [70].

4.2.1.4. User Acceptance

Research question: Is the driver more inclined to accept slower speed values if the driving task is carried out by the Highway Chauffeur system? Does he ignore the speed suggestion, sure that the Traffic Jam Chauffeur is going to face the queue for him, instead?

If the driver can choose the speed kept by the HC vehicle, overriding the suggested speed limit, it should be evaluated what behaviour does he or she assume. A human driver can, in fact, both accept willingly a reduced speed value, while engaged in a secondary task, and favour an earlier approach to the queue that is going to be faced by the Traffic Jam Chauffeur.

➤ Is the driver (more) compliant with the suggested speed limit?

It should be evaluated if the driver accepts willingly reduced speed value, if that is the case, the HC system should be able to comply as precisely as possible with the suggested speed limit.

Assessment instrument

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

Survey's Outputs

The following indicators should be collected after surveys:

- Situation awareness
- Knowledge about the Highway Chauffeur system and its capabilities
- Knowledge about the Traffic Jam Chauffeur system and its capabilities
- Perception of the time spent in queue

4.2.2. Embedded VMS “free text”

This Use Case allows the “free text” message showed on a VMS (e.g. Variable Text Panel) to be displayed on-board, a completely new message can be delivered too and in the same way (virtual VMS). The expected benefits concern mostly an improved traffic management by the means of a more effective message delivery, an enhanced compliance and augmented comfort for the driver. Even if not explicitly stated in [70], this use case can deliver information directly to the Highway Chauffeur system, offering redundancy to what is perceived through the sensors. The equipped cameras, in fact, could miss some information because, typically, VMS are placed higher than the rest of the other road features and can fall outside their range, especially if the visibility conditions are hindered (because, for example, heavy rain, fog or light conditions). Thus, the Highway Chauffeur system can show this information to the human driver through the HMI or can exploit the added knowledge to adapt its driving style without bothering the human driver.

The information relevant specifically for the HC vehicle and usually delivered by the means of the VMS can be:

- Traffic Management plan - Congestion
- Travel time
- Speed advice
- Accidents
- Roadworks
- Debris on roadway
- Closure of the whole carriageway

As can be easily realized, these situations are also covered by dedicated Use Cases and C-ITS messages, analysed in this chapter. For this reason, there will not be an in depth analysis for each one of the four identified impact areas, it should only be highlighted how an improved “situational awareness” for the HC vehicle is almost always beneficial and the achievable benefits are similar to the ones described along this chapter.

Because the scenarios are pretty similar to the ones defined in other use cases, the considerations presented in these paragraphs can be considered valid for this use case too.

4.2.3. Other Signage Information

This Use Case broadcasts to the vehicle information concerning physical signage alongside the road and approached during the travel. Besides, information from the Traffic Control Centre or VMS (other than the information presented in 4.2.2) can be received too. In [70] autonomous driving is explicitly mentioned to exploit this Use Case.

The information relevant specifically for the HC vehicle and delivered by the means of this Use Case can be:

- Speed advice which can be related not only to traffic jam and congestion but also to adverse weather conditions and reduced road adhesion
- Overtaking prohibition, this information can support the HC vehicle offering redundancy to the physical signs detection performed by the perceiving system
- Lane advice or information about closed driving lanes

As can be easily realized, these situations are also covered by dedicated Use Cases and C-ITS messages, analysed in this chapter. For this reason, there will not be an in depth analysis for each one of the four identified impact areas, it should on be highlighted how an improved “situational awareness” for the HC vehicle is almost always beneficial and that some sort of redundancy concerning the perception of physical road signs can prove to be really useful (supporting the system when a signal is vandalized, ruined or covered by vegetation).

Because the scenarios are pretty similar to the ones defined in other use cases, the considerations presented in these paragraphs can be considered valid for this use case too.

4.3. Hazardous Location Notification (HLN)

Service Description

On the basis on what is stated in [71], the following considerations can be made. This service is intended to provide warnings to road users approaching a series of potentially hazardous events on the road. The information delivered concerns the location, the type of the hazard and, if available, also the duration of the event. The Use Cases considered in their joint implementation with the Highway Chauffeur System are:

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

Only for this service's Use Cases, a clustering approach is going to be followed and the Use Cases sharing similar research questions related to the Highway Chauffeur system are going to be examined in the same paragraph.

The benefits that the service alone is meant to achieve are mainly bound to safety; an increased attention, an adaptation of the driving speed and a more efficient lane changing (if needed) are the expected behaviour among informed road users.

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

The drivers know, by the means of the C-ITS service, of a dangerous situation along the road in advance. If the information is detailed enough, the HC vehicle can adapt its speed or change lane earlier, exploiting increased time gaps found upstream the dangerous section. This way the system can avoid being stuck behind a slow vehicle or a generic obstacle, preventing itself from the need to perform sudden lane changing maneuvers or recall the driver back into the driving loop. Moreover, an increased safety can be obtained, providing the HC vehicle with details about the hazardous location that can be used by the software to validate or verify what is perceived through the sensors. This could be especially useful in scenarios strongly characterized by a

random nature such as Obstacle on the road (automation doesn't perform well in random scenarios, funny and explanatory is the "teenagers in zombie kangaroo costumes"³ example reported in [85]). It should also be mentioned how, at the state of the art, accidents involving persons on the road are still possible (e.g. the Arizona accident happened in march 2018, involving an Uber self-driving vehicle and a pedestrian) and that additional information about persons on the road can improve the safety of the system, especially on highways where pedestrians are not a recurring presence.

4.3.1.1. Traffic Efficiency

Research question: Does the information forwarded in advance improve the driving performance of the HC vehicle?

Having an improved situational awareness leads to better driving performance of human drivers, a similar consideration can be made concerning the Highway Chauffeur system. In fact, knowing about a slow or stationary vehicle on the road ahead can help the HC vehicle in the overtaking maneuver (easing the task for more conservative algorithms) or can anticipate its lane changing maneuver (fostering maneuvers performed with increased time gaps on the other lane, which have a reduced impact on the following vehicles and on the shockwaves perturbation and propagation upstream). The same considerations can be made about an accident zone if the whole carriageway isn't involved. If an obstacle on the road is present, instead, the information provided by the C-ITS can help the automated system adopt the right strategy to face the issue. As showed in [20], two main type of collision can arise in this scenario: collision with the obstacle and collision on the other lane caused by a high speed difference between the two lanes. The information can both foster an earlier lane change or provide redundancy to the sensors that could perceive late the obstacle, especially if the preceding vehicle covers it and performs a lane change maneuver suddenly.

- *How does the lane change point vary (if the lane of the event is specified)?*
- Are the accomplished lane changing maneuvers smoother?*

Knowing in advance about a dangerous event hindering one or more lanes (but not the whole carriageway) should help the HC vehicle performing the lane changing maneuver, easing the search for a safe gap on the other lane and its interactions with the

³ "In addition, children sometimes dress in animal costumes, and adolescents in zombie variations. Most drivers can understand such risks. If I say, "Watch out for a group of teenagers in zombie kangaroo costumes," you could probably understand the threat since you too were once a playful youth, but a computer would be flummoxed: that situation would be too unusual to be in the standard risk database, so the vehicle would either miss-categorize it, perhaps treating costumed fun-seekers as injured crash victims or a riotous mob, or simply stop and wait for human instructions." [85]

surrounding traffic. The same considerations can be made about its overtaking maneuver performed to surpass a slow or stationary vehicle.

➤ *Does the average speed decrease?*

The increased awareness of the system about a potentially dangerous event ahead could induce more cautious driving behaviour and speed values lower than the ones set by the driver. This, in turn, should lead to fewer sudden and relevant braking when the event is reached, thus obtaining less perturbations upstream. Moreover, as stated in [71], a speed advice could be provided to the HC vehicle that could comply and adapt its driving behaviour.

➤ *If the slow or stationary vehicle is the source of the V2V message, does the HC vehicle perform a smoother braking while approaching the broken-down vehicle?*

It could also happen that a vehicle driving further ahead suffers from a technical failure while preceding the HC vehicle. If that is the case and the broken-down vehicle is able to broadcast the C-ITS message, does the HC vehicle perform a smoother braking, causing fewer and smaller perturbations upstream the traffic flow?

Assessment instrument

Assessing the environmental impacts should be accomplished both through field tests and modeling works. The former can be used to evaluate the energy consumption of the HC vehicle and behavioural inputs (both of the HC vehicle and of the human drivers) to design more accurate modeling works, aimed to assess the environmental impacts of different percentages of HC vehicles among the traffic flow. A fair share of HC vehicles, in fact, can also ease the congestion often arising with the events included in Cluster 1, if the right ACC strategies are implemented. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. Examples of this kind of specifications can be found in the dedicated C-Roads documents [71]. The baseline scenarios should consider both HC vehicles unequipped for the cooperative message reception and manually driven vehicles (both equipped and unequipped). If the OEMs design the HMI to show only some of these information, which ones are displayed and when it happens must be specified. Also, each Use Case included in the cluster should be evaluated separately.

4.3.1.2. Safety

Research question: Does the information forwarded to the system grant some sort of redundancy to the perceiving system?

The Use Cases included in Cluster 1 are, by their nature, aleatory and barely foreseeable. Therefore, the perceiving system must detect the hazard promptly and steadily to allow the HC vehicle to travel safely across the dangerous section. Moreover, the situation that should be perceived can have peculiar features that could prove to be challenging for the perceiving system to sense and decipher in the right way (e.g. an accident could have just happened and could be signaled only through the emergency warning triangle or not signaled at all). Knowing about the accident in advance can grant to the Highway Chauffeur system an additional information source and some redundancy to the function conducted by the perceiving system. Similar considerations can be made for the other Use Cases included in Cluster 1. It should be highlighted how, in safety critical situations, the issue of functional safety and compliance of V2X cooperative applications to the ISO 26262 become more relevant. It should be clear when considering one scenario in which the automated system changes its behaviour based on V2X communication (e.g. changes lane).

➤ *Does the number pre-crash scenarios lower thanks to the information granted by the C-ITS?*

The main issue with the safety assessment could be the unsuitableness of field tests for the comparison of the number of accidents between scenarios (hopefully, during a field test rather limited both in time and space, the number of accidents should be insufficient). Thus, in order to assess the impact of the redundancy achieved through the C-ITS, the number of pre-crash scenarios should be employed. The additional information provided by the C-ITS message should lead to fewer scenarios in which critical values of TTC and/or Brake Threat Number or analogous metrics are reached.

Research question: Does the information forwarded in advance to the system foster smoother braking and lane changing maneuvers, thus promoting a safer driving regime?

If the C-ITS message is detailed enough and reveals how many lanes are hindered by the accident/the obstacle or on which lane the broken-down vehicle is located, the HC vehicle can perform the lane changing maneuver in advance. As mentioned in the previous paragraphs, knowing in advance about the need to change lane increases the number of disposable gaps on the other lane before arriving to the lane closure and allows the HC vehicle to perform the

maneuver exploiting the wider ones. This should result in increased TTC times between the HC vehicle and the other ones on the other lane.

- *Does the information granted in advance prevent the HC vehicle from colliding with the signalized hindrance or with the surrounding vehicles (e.g. during an evasive maneuver)?*

An obstacle on the road can be concealed by the preceding vehicle and appear suddenly to the HC vehicle that must perceive it and avoid it accordingly in a short time span. The knowledge about the exact position of the danger can increase the safety for the HC vehicle even if a lane change maneuver can't be performed in advance (for example because of the density of the surrounding traffic flow). Smoother braking and/or lane changes should lower the number of collisions with the surrounding vehicles while knowing about the obstacle's exact position should prevent the HC vehicle from colliding with it. From similar scenarios tested in [20], the probability of avoiding an accident is 28,3% higher and the speed difference between vehicles involved in collisions is 15% lower with automated driving. A work that specifically addresses the opportunities granted by V2X communications when approaching a stationary vehicle is [94].

- *Does the HC vehicle adapt its speed to be more compliant with the suggested speed limit?*

Thanks to the received information, the HC vehicle can adapt its speed without the driver's intervention, overriding the desired speed value set in the ACC (or it could ask the driver informing it about the warning, instead, the suggested speed limit is not mandatory and the adopted strategy lies in the OEM's hands). The speed adaptation should lead to smoother braking and lower risks of rear-end collisions, if a speed advice is provided by the means of the C-ITS. Besides, if a person is on the road, lower speed values should grant to the perceiving system more time to sense his or her presence and to the software to elaborate the information and act accordingly.

- *Is the take-over transition carried out in a smoother and safer way?*

Should the Highway Chauffeur system deem the situation signalized through the C-ITS to be out its ODD (because, for example, lightly adverse weather or light conditions), the information forwarded in advance should lead to smoother and safer take-over maneuvers, carried out in a way that allows the human driver to be fully re-engaged once the dangerous event is reached.

Assessment instrument

The Safety evaluation should be done mainly through modeling or bibliographical review, but can't be complete without field tests able to validate the designed system and how it interacts with the surrounding traffic. The capability of the HC system in responding to unforeseen scenarios related to hazardous locations (such as accidents, slow or stationary vehicles or obstacles on the road) should be assessed with a huge number of kilometres driven. In designing these tests, guidelines like the ones drawn from the NHTSA can be considered. In [45], for example, the main safety-related design aspects are listed to be considered when deploying automated systems on public roadways. Besides, field tests or virtual testbeds can be employed to assess behavioural inputs to design appropriate car following models and safety critical scenarios in modeling works. Other behavioural subjects that can be investigated, even with more local field tests, concern the control transition between the HC system and the human driver, take-over time and the relationship between the two authorities on-board (the human driver and the HC system). When designing field tests involving hazardous locations such as the ones included in Cluster 1, the right set of information to broadcast to the driver to maximize its capability to re-acquire situational awareness should be investigated (e.g. distance from the event, number of closed lanes, suggested speed limits, etc.). The shift in control should be evaluate prior to field tests by the means of digital testbeds, to guarantee a safe transition time in each scenario. The baseline scenario should consider HC vehicles unequipped for the cooperative message reception. The data collected should also be relevant to investigate any incidents that may occur (achievable through Event Data Recorders) and the pre-crash scenarios detected (on the basis of the safety-related metrics) should be recorded. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. Examples of this kind of specifications can be found in the dedicated C-Roads documents [71]. As long as a more cautious speed regime is concerned, both Nilsson's Power Model and an exponential model can be employed [77].

4.3.1.3. Environment

Research question: Does the information granted by the service promote a more efficient driving while approaching the hazardous locations included in Cluster 1?

As stated in 4.3.1.1, an earlier notification leads to a more efficient driving and to smoother maneuvers carried out by the HC vehicle. Smoother maneuvers lower the energy consumption

needed to be accomplished and have a reduced impact on the surrounding traffic flow, fostering an overall more energy efficient driving.

- *How does the lane change point vary (if the lane of the event is specified)?
Are the accomplished lane changing maneuvers smoother?*

If the hindered lanes are signalled to the Highway Chauffeur system, the control algorithm can search earlier for wider time gaps on the other lanes, thus increasing the odds of performing such maneuvers without adversely affecting the traffic flow upstream.

- *Does the HC vehicle perform smoother braking thanks to the C-ITS message?*

If the HC vehicle adapts its speed while approaching the dangerous location, a smoother brake action is needed to respond to the event once it is reached. Smoother braking, in turn, affect less the traffic flow upstream, fostering a more energy efficient driving regime. Besides, if a slow or stationary vehicle is the source of the V2V message, the receiving HC vehicle knows in advance about its situation and can perform a smoother braking while approaching it. Moreover, a take-over maneuver triggered by the C-ITS message and started in advance should be smoother and involve less abrupt braking performed by the human driver.

Assessment instrument

Assessing the environmental impacts should be accomplished both through field tests and modeling works. The former can be used to evaluate the energy consumption of the HC vehicle and behavioural inputs (both of the HC vehicle and of the human drivers) to design more accurate modeling works, aimed to assess the environmental impacts of different percentages of HC vehicles among the traffic flow. A fair share of HC vehicles, in fact, can also ease the congestion often arising with the events included in Cluster 1, if the right ACC strategies are implemented. The baseline scenario should consider HC vehicles unequipped for the cooperative message reception and human driven vehicles (both equipped and unequipped), other scenarios that could be compared considers different time gaps and, potentially, adaptation of these value to apply traffic control strategies similar to the ones in [32,57]. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. Examples of this kind of specifications can be found in the dedicated C-Roads documents [71].

4.3.1.4. User Acceptance

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

Re-engaging the driving task after a moderately long time involved in a secondary task can potentially induce a feeling of urgency and/or danger in the human driver, thus worsening the whole driving experience. If the Highway Chauffeur system faces the hazardous event without re-engaging the human driver, the C-ITS message can avoid evasive maneuvers performed abruptly, for example if an obstacle on the road becomes suddenly visible (as mentioned in 4.3.1.2). These maneuvers are by no means more abrupt than the ones performed by the human driver but can be perceived as dangerous by a driver involved in a secondary task and not in control. If the Highway Chauffeur system must re-engage the human driver to face the hazardous event, a C-ITS message received in advance and delivering a more complete set of information should help the driver reacquire situational awareness easily and approach the hazardous location with confidence. It should be noted that these considerations depend also on when and how the message is displayed by the system according to the OEMs design.

Assessment instrument

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

Survey's Outputs

The following indicators should be collected after surveys:

- Situation awareness
- Knowledge about the Highway Chauffeur system and its capabilities
- Problem perception related to the approached hazardous location
- Perceived threats for the driver himself or for the workers on the road
- Perceived comfort during the maneuvers carried out by the HC vehicle, while passing the hazardous location

4.3.2. Cluster 2: Traffic Jam Ahead

The drivers know about a traffic jam ahead their route thanks to the information sent by the road operator. The position, the length of the traffic jam and the section/lanes concerned are broadcasted, if the information is available. The promptness and precision of the message should be higher than conventional means, which means that preventive maneuvers can be

accomplished in a smoother and more efficient way. Moreover, informing about the end of a queue allows the approaching drivers to adapt their speed and have an improved situational awareness, increasing Safety. Both Traffic Efficiency, Environment and Safety benefits are expected to be achieved through the Traffic Jam Ahead Use Case.

4.3.2.1. Traffic Efficiency

Research question: Does the HC vehicle adapt its “behavior” because of the warning/information given by the service?

Knowing about the position of the queue could impact on the driving of the HC vehicle, resulting both in lower speed values and earlier lane changing maneuvers which, in turn, should translate into smoother braking and lane changes. Besides, if the time gaps and the acceleration regime kept by the HC vehicle can adapt to the values suggested by a Traffic Control Centre, as hypothesized for example in [32], an additional benefit can be achieved for the whole traffic flow.

➤ *Is the HC vehicle’s speed (more) compliant with the suggested speed limit?*

If the HC vehicle complies with the suggested speed limit, receiving the value continuously updated as soon as the downstream traffic conditions change means a readier adaptation when compared, for example, to the punctual information granted by Variable Message Signs. Moreover, having the automation applying the speed adaptation means that no flaws in the desired longitudinal regime are due to possible distraction or tiredness of the human driver. It should be evaluated how, having a fair share of automated vehicles upstream the traffic flow and driving almost perfectly with the desired speed value, impacts on the overall traffic flow. Besides, if the HC vehicle adapts its speed and knows about the approximated queue position, it should be able to avoid harsh braking, thus affecting less the traffic flow upstream.

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

If the lanes hindered by the queue are signaled through the C-ITS service, the HC vehicle can change lane as soon as it finds a suitable gap on the other lane, increasing the odds of finding a gap wide enough to minimize the impact of this maneuver on the traffic flow upstream (thus limiting shockwave propagation).

➤ *Does the Highway Chauffeur system follow the traffic control strategies suggested by the Traffic Control Centre or by the road operator? Does it*

adapt its time gaps and acceleration values to respond to the surrounding traffic conditions?

As mentioned in 2.2, the Highway Chauffeur system can adapt the parameters defining its longitudinal control law accordingly to external inputs (i.e. through I2V communications) or to what its perceived through its sensors. This adaptation can begin while approaching a queue. In both cases, having the HC vehicles driving in a way that is beneficial for the traffic flow leads to more regular flow conditions and to earlier returns to the decongested state.

➤ *How do the instant speed fluctuations change?*

If, through V2V communications, the HC vehicles receives the braking actions of the vehicle ahead the one preceding itself (thus not perceivable by its sensors) it could respond to these braking in a more efficient way (bringing its braking action forward the one performed by the vehicle ahead of it).

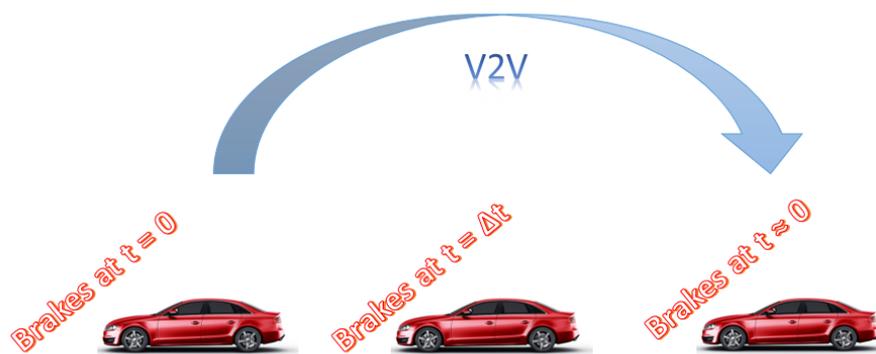


Figure 3 - V2V & Traffic Jam Ahead

Assessment instrument

The impacts can be assessed both through field tests and modeling works (especially for higher level of market penetration) to evaluate the impacts on the overall traffic flow. Baseline scenarios could be the one in which no information is forwarded to the HC vehicle and the one in which the same information is given through VMS, also scenarios in which both time gaps and accelerations performed by the HC vehicle in queue are tailored to maximize traffic efficiency rather than the driver comfort should be evaluated. Moreover, the performance of the HC vehicle should be compared to the one of the human driven vehicle. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as

communication ranges, the means of broadcasting and the information transmitted. Examples of this kind of specifications can be found in the dedicated C-Roads documents [71].

4.3.2.2. Safety

Research question: Does the information provided by the C-ITS prevent rear end collisions between the HC vehicle and the end of the queue?

One of the expected benefits of this Use Case is an increased safety and a decreased number of accidents thanks both to a more precise localization of the end of the queue and to the speed adaptation that the receiving vehicle performs, knowing about the dangerous location ahead. The HC vehicle will probably be equipped with the Autonomous Emergency Braking, able alone to prevent most of the rear-end collisions with the end of the queue, performing abrupt maneuvers that could cause collisions with the vehicles behind it, though. Knowing about the end of the queue should foster smoother braking and lower the odds of collisions between the HC vehicles and the ones behind it. Besides, if a vehicle that brakes at the end of the queue is equipped in a way that allows it to broadcast this information, the HC vehicle can receive this information even if the braking vehicle is not the preceding one and respond braking in a more efficient way. It should be noted that said benefits are also obtainable by a human driven vehicle equipped for the reception of cooperative messages, even if in a less efficient way.

➤ *Is the HC vehicle's speed (more) compliant with the suggested value?*

If the HC vehicle adapts its speed in advance, the braking at the end of the queue should be smoother and, thus, safer.

➤ *Does the HC vehicle perform a lane change maneuver to avoid the queue? Is this lane changing maneuver smoother?*

If the queue is limited to a single lane (or doesn't involve the whole carriageway), the HC vehicle can surpass the queue resorting to a lane changing maneuver accomplished in advance, possibly with wider time gaps and in a safer way.

➤ *How do the instant speed fluctuations change?*

If, through V2V communications, the HC vehicles receives the braking actions of the vehicle ahead the one preceding itself (thus not perceivable by its sensors) it could respond to these braking in a more efficient way, also promoting safety (bringing its braking action forward the one performed by the vehicle ahead of it).

Assessment instrument

The Safety evaluation should be done mainly through modeling or bibliographical review, but can't be complete without field tests able to validate the designed system and how it interacts with the encountered traffic jams. In designing these tests, guidelines like the ones drawn from the NHTSA can be considered. In [45], for example, the main safety-related design aspects are listed to be considered when deploying automated systems on public roadways. Besides, field tests or virtual testbeds can be employed to assess behavioural inputs to design appropriate car following models and safety critical scenarios in modeling works. The baseline scenarios should consider HC vehicles unequipped for the cooperative message reception and human driven vehicles (both equipped and unequipped), other scenarios should include the information forwarded by the means of VMS or not forwarded at all. The data collected should also be relevant to investigate any incidents that may occur (achievable through Event Data Recorders) and the pre-crash scenarios detected (on the basis of the safety-related metrics) should be recorded. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. Examples of this kind of specifications can be found in the dedicated C-Roads documents [71].

4.3.2.3. Environment

Research question: Does the information about the queue allow the HC vehicle to drive in a more energy efficient way?

The Traffic Jam Ahead Use Case can reduce the HC vehicle's energy consumption (and the related emissions) both by fostering smoother braking actions and by increasing the number of HC vehicles able to avoid the queue (if the whole carriageway isn't involved). It should be noted that both these benefits are achievable also by a human driven vehicle, even if not in the same quantity.

➤ *Is the HC vehicle's speed (more) compliant with the suggested value?*

If the HC vehicle adapts its speed in advance, the braking at the end of the queue should be smoother and, thus, impact less on the traffic flow upstream and on the energy consumption of the HC vehicle itself.

➤ *Does the HC vehicle perform a lane change maneuver to avoid the queue? Is this lane changing maneuver smoother?*

If the queue is limited to a single lane (or doesn't involve the whole carriageway), the HC vehicle can surpass the queue resorting to a lane changing maneuver accomplished in

advance, possibly with wider time gaps and in a smoother and more energy efficient way.

- *How do the instant speed fluctuations change thanks to the messages received?*

If, through V2V communications, the HC vehicles receives the braking actions of the vehicle ahead the one preceding itself (thus not perceivable by its sensors) it could respond to these braking in a more efficient way, thus limiting fuel consumption (bringing its braking action forward the one performed by the vehicle ahead of it).

- *Does the Highway Chauffeur system adapt its longitudinal control law once the C-ITS message is received and the queue is signalized?*

As mentioned in 2.2, a vehicle equipped with the ACC system can adapt its accelerations and the kept time gap already while approaching the queue. These control strategies can be tailored to ease the congestion, improve the traffic flow and promote an overall more energy efficient driving regime (thus reducing emissions levels).

Assessment instrument

Assessing the environmental impacts should be accomplished both through field tests and modeling works. The former can be used to evaluate the energy consumption of the HC vehicle and behavioural inputs (both of the HC vehicle and of the human drivers) to design more accurate modeling works, aimed to assess the environmental impacts of different percentages of HC vehicles among the queue. The baseline scenario should consider HC vehicles unequipped for the cooperative message reception, other scenarios that could be compared considers different time gaps and, potentially, adaptation of these value to apply traffic control strategies similar to the ones in [32,57], triggered by the message delivered by the Traffic Jam Ahead Use Case. Besides, the energy consumption achieved by the HC vehicle in these scenarios should be compared to the one achieved in the same scenarios by a human driven vehicle. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. Examples of this kind of specifications can be found in the dedicated C-Roads documents [71].

4.3.2.4. User Acceptance

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

Unless some factors external to the ODD occurs, the Highway Chauffeur system should be able to face the upcoming traffic jam without re-engaging the human driver. An earlier notification to the system leads to smoother maneuvers performed by the automated. This, in turn, should improve the feeling of safety and comfort experienced by the driver, improving User Acceptance.

Assessment instrument

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

Survey's Outputs

The following indicators should be collected after surveys:

- Situation awareness
- Knowledge about the Highway Chauffeur system and its capabilities
- Perceived comfort during the maneuvers carried out by the HC vehicle, while passing the hazardous location
- Propensity to let the Highway Chauffeur system adapt the values of speed and time gap, according to the situation of the surrounding traffic

4.3.3. Cluster 3: Weather Condition Warning – Temporarily slippery road

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

be expected, though, especially if the information granted allows the HC vehicle to expand its ODD or makes the take-over maneuver smoother.

In this paragraph the following assumption are going to be made:

1. if an HC vehicle drives through a puddle of unidentified liquid, the system asks the human driver to re-engage the driving task.
2. If the HC vehicle receives information about adverse weather conditions hindering visibility or road adhesion, the system asks the human driver to re-engage the driving task.

The latter assumption could be more conservative than needed, LIDARs and radars technologies should be already able to face most of the adverse weather conditions, at least for the time needed to the driver to take back control. Nevertheless, the lack of redundancy caused by the inability of cameras to see through rain, snow, fog or some light conditions could involve unacceptable level of risks, therefore a precise definition of the system ODD in relation to weather conditions must be obtained before deploying the system on public roads for field tests.

“First-generation automated vehicle systems will most likely disable under heavy rain (poor visibility) conditions using rain detection systems already available on production cars. The ability to transfer control back to the driver during these cases (e.g., instantaneous heavy rain in a thunderstorm) will be critical.” [39]

Another example is the google self-driving car that can assess how rain can affect its ability to drive, adapt its driving behaviour (speed, decelerations, etc.) but, if the rain is severe enough, the car automatically pull over and wait until conditions improve [81]. It is also worth mentioning the DENSE 24/7 project aimed to tackle the challenges related to the interaction between the perceiving system and adverse weather conditions, developing an all-weather sensor suite [79,80].

4.3.3.1. Traffic Efficiency

Research question: Does the information regarding the slippery road allow the HC vehicle to change lane and avoid the liquid?

If the information delivered through the C-ITS is detailed enough to identify the lanes hindered by the spillage (and the carriageway isn't totally affected by the event), the HC vehicle tries to

change lane and avoid driving through the liquid. Having more time to carry out the lane changing maneuver means that wider gaps can be identified and exploited, thus affecting less the traffic flow upstream. Besides, allowing the vehicle to change lane and to avoid the spillage increases the number of kilometres driven with the automated system engaged and avoids the take-over maneuver which can affect adversely the surrounding traffic flow. If the whole carriageway is involved, instead, the Highway Chauffeur system can issue a take-over request to the driver in advance, thus fostering a smoother transition in control, less abrupt braking and lesser shockwaves propagated upstream the traffic flow.

➤ *Does the HC vehicle surpass the hazardous section without re-engaging the driver?*

If the HC vehicle knows in advance about the spillage, the odds for it to surpass said spillage without driving through it increase. Thus, the take-over maneuver is avoided and the number of kilometres driven with the automated system engaged (therefore, driven more efficiently) increase.

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

A lane change maneuver accomplished in advance and with wider time gaps should have reduced impacts on the surrounding traffic flow and produce lesser shockwaves upstream.

➤ *Is the take-over transition smoother?*

Knowing about the spillage in advance and about the necessity to re-engage the driver in the driving loop should allow the Highway Chauffeur system to issue the take-over request in advance, fostering a smoother transition in control, avoiding harsh braking and thus impacting less on the surrounding traffic flow.

Research question: Does the information concerning weather conditions forwarded in advance to the HC vehicle foster a take-over transition accomplished in advance and in a smoother way?

Especially in some of the European countries, adverse weather conditions can arise suddenly, thus not granting enough time for a smooth take-over transition (that could be needed, for example, if a strong snowfall hides lane markings and/or reduces visibility). Knowing in advance about the event allows the Highway Chauffeur system to issue a take-over request while the weather is still included in the system ODD. Besides, accomplishing the maneuver before reaching the adverse weather leaves more time to the driver that should be more relaxed while

taking back control (if the request is issued together with the adverse weather the driver can be more alarmed and accomplish the maneuver in a more abrupt way).

- *Does the driver re-engage the driving task without braking or swerving, in time to reach the signalled section with a fully regained situational awareness?*

If the take-over request is issued as soon as the adverse weather condition arises, an inattentive driver could be induced into re-engaging the driving task in a more urgent and sudden way, thus possibly performing abrupt braking or swerving and perturbing the surrounding traffic flow.

- *Does a vehicle suddenly made “blind” by an adverse weather condition take itself to the nearest safe state (e.g. stop on the hard shoulder)? Does the message forwarded by the Adverse Weather Condition Use Case prevent this kind of scenario?*

If the time for a take-over transition isn't guaranteed, the HC vehicle could take itself to the nearest safe state, for example stopping itself on the hard shoulder. Obviously such a situation could be both dangerous and inefficient, potentially imposing braking or deceleration on the following vehicles. Moreover, when the human driver re-engage the driving task and restarts from the hard shoulder, the vehicle must accelerate starting from a null speed value which is both dangerous and inefficient for the whole traffic flow. If the C-ITS prevents the HC vehicle from being surprised by sudden adverse weather conditions, these kind of situations should be avoided.

- *Does the HC vehicle surpass the hazardous section without re-engaging the driver?*

Even if the adverse weather conditions aren't so critical to hinder the capability of the perceiving system, some related information can be challenging to retrieve (e.g. reduced road adhesion due to black ice). If the message broadcasted by the C-ITS is detailed enough to include these details, a safe driving could be achieved without disengaging the automated system. Thus, the take-over maneuver is avoided and the number of kilometres driven with the automated system engaged (therefore, driven more efficiently) increase.

Assessment instrument

To assess the jointed impacts, both field tests (employable to evaluate the system robustness when facing adverse weather conditions or the capability of avoiding spillages on the road) and modeling works can be employed. During the field test design, for each weather scenario considered the ODD should be clearly defined to avoid dangerous situations, moreover the weather condition should be measured with appropriate metrics (e.g. through rain gauges or weather sensors). The perceiving system should be fully validated and each equipped sensor should be analysed (e.g. if the HC vehicle is equipped with a mobile Road State Sensor [80], some issues bound to road adhesion become less critical). Redundancy in the perceiving system should always be guaranteed, if that is not possible, the system should be able to issue a take-over request or take itself to the nearest safe state with acceptable levels of risk. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted, the coverage of the service during adverse weather condition should be assessed. Examples of this kind of specifications can be found in the dedicated C-Roads documents [71]. Moreover, each Use Case included in the cluster should be evaluated separately.

4.3.3.2. Safety

Research question: Does the information forwarded in advance foster safer maneuvers before and while approaching a spillage?

Knowing about the need to perform the lane change to avoid the slippery road surface or the need to re-engage the driver before driving through an unidentified liquid should allow the Highway Chauffeur system to perform smoother lane changing or take-over maneuvers. This, in turn, should lower the number of scenario in which critical TTC values or abrupt braking are reached.

- *Does the lane change point vary? Is the lane changing maneuver smoother? (if the lane of the event is signalled)*

Knowing about the needed lane change maneuver should allow the HC vehicle to start searching for a gap wide enough in advance, which in turn should increase the odds of performing such maneuver with increased time gaps and lower risks of collision with vehicles on the other lane.

- *If the HC vehicle can't avoid the spillage, is the take-over maneuver accomplished in advance, in a smoother and safer way?*

If an unidentified liquid is spilled on the road, a human driver taking back control and braking abruptly can be considered a safety critical scenario. The information provided by the C-ITS should foster safer take-over maneuvers carried out in advance and prevent these kind of scenarios.

- *Does the HC vehicle's speed decreases before reaching the slippery section? Does the information prevent the HC vehicle from passing through the spillage at high velocity?*

If a lane change maneuver can't be accomplished, even with the aid of the C-ITS message, or the spillage involves the whole carriageway the HC vehicle should decelerate in a smoother way knowing the position of the spillage (which could be not detected at all by the perceiving system if the light conditions aren't optimal).

Research question: Does the C-ITS message prevent the HC vehicle from suddenly finding itself out of the intended ODD?

If the adverse weather condition arises abruptly once reached a certain section, the HC vehicle could find itself suddenly driving out of its ODD. In this case the vehicle can both try to re-engage the human driver in the driving loop or take itself to the nearest safe state, that can be, for example, a complete stop on the hard shoulder. All of the above scenario can prove to be safety critical and could be prevented if the message broadcasted by the C-ITS is received in advance and the human driver is fully in control when the adverse weather condition is reached.

- *Does the received information give details about road adhesion that the perceiving system isn't able to detect?*

Road adhesion can be affected by weather in different ways, some of which are hardly detectable both by the human eye and the perceiving system (e.g. black ice). If the system isn't equipped, for example, with a mobile Road State Sensor [80], receiving in advance information about the reduced road adhesion can prevent the HC vehicle from performing abrupt braking or steering. Moreover, the take-over maneuver, if needed, can be issued accordingly, in order to avoid dangerous interventions from the human driver re-entering the driving loop.

- *Does the take-over maneuver happen in a smoother and safer way?*

If the take-over maneuver is accomplished in advance, before reaching the section interested by the adverse weather condition, different safety critical scenarios can be avoided. In addition to a reduction of abrupt braking on slippery surfaces, scenarios in

which the HC vehicle brakes abruptly due to a take-over maneuver and a following vehicle rear-ends because of the reduced visibility are avoided. Moreover, not issuing a take-over request where the road adhesion is already compromised reduces the risks bound to the inevitable swerving performed by the human driver re-engaging the driving loop.

➤ *Does the average speed decrease?*

Even if the HC vehicle can drive through the adverse weather section, knowing in advance about the adverse weather condition and the level of road adhesion should allow the HC vehicle to decelerate and reach the dangerous section with an appropriate driving regime, thus fostering safety. Moreover, having HC vehicles driving slower upstream the congested front should impose lower speed values also to the traditionally driven vehicles that would be forced to overtake to maintain their desired speed value (likely higher than the suggested one). On the other hand it should be evaluated how many of these traditionally driven vehicles would decide to overtake, if their number is high enough, negative effects on the overall safety would be obtained.

➤ *Does a vehicle suddenly made “blind” by an adverse weather condition take itself to the nearest safe state (e.g. stop on the hard shoulder)? Does the message forwarded by the Adverse Weather Condition Use Case prevent this kind of scenario?*

If the Highway Chauffeur system finds itself suddenly out of the intended ODD and deems too time consuming issuing a take-over request, it could take itself to the nearest safe state. The worst case scenario is an HC vehicle simply stopping in the middle of the road but an HC vehicle able to reach the hard shoulder before stopping constitutes a safety critical scenario too. Especially if the visibility is hindered, in fact, the human driver taking back control of the vehicle must re-start from a null speed value and re-enter the right lane, which could prove to be both challenging and dangerous. If the C-ITS message is received in advance, the take-over maneuver can happen safely and at a slow pace, before reaching the dangerous location.

Assessment instruments

The Safety evaluation should be done mainly through modeling or bibliographical review, but can't be complete without field tests able to validate the designed system and how it interacts with the encountered weather conditions. The capability of the HC system to respond to

unforeseen scenarios related to fog, rain, snow or ice (which could hinder both visibility and road adhesion) should be assessed with a huge number of kilometres driven for each one of these meteorological event. In designing these tests, guidelines like the ones drawn from the NHTSA can be considered. In [45], for example, the main safety-related design aspects are listed to be considered when deploying automated systems on public roadways. Besides, the ODD of the system deployed on the road should be precisely defined in relation to each one of the meteorological event and of the perceiving system and its robustness. Other behavioural subjects that can be investigated, even with more local field tests, concern the control transition between the HC system and the human driver, take-over time and the relationship between the two authorities on-board (the human driver and the HC system). When designing field tests involving hazardous locations such as the ones included in Cluster 3, the right set of information to broadcast to the driver to maximize its capability to re-take situational awareness should be investigated (e.g. distance from the event, type and intensity of the event, suggested speed limits, etc.). The shift in control should be evaluated prior to field tests by the means of digital testbeds, to guarantee a safe transition time in each scenario. The baseline scenario should consider HC vehicles unequipped for the cooperative message reception and human driven vehicles (both equipped and unequipped), another scenario that should be compared is the one that considers the possible degradation of the automated function or the robustness of the designed fall-back solutions and of the system in general. The data collected should also be relevant to investigate any incidents that may occur (achievable through Event Data Recorders) and the pre-crash scenarios detected (on the basis of the safety-related metrics) should be recorded. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. Examples of this kind of specifications can be found in the dedicated C-Roads documents [70].

4.3.3.3. Environment

Research question: Does the information forwarded by the service foster more energy efficient maneuvers carried out by an HC vehicle?

Knowing in advance about the need to perform a lane changing maneuver to avoid a spillage or a take-over maneuver before reaching an intense rain should foster smoother maneuvers performed by the HC vehicle, more energy efficient for the vehicle itself and less impacting on the surrounding traffic flow.

- *Does the HC vehicle perform the lane changing maneuver in a smoother way to avoid the spillage?*

Knowing in advance about the need to perform the lane changing maneuver should allow the HC vehicle to perform the maneuver as soon as possible, finding wider gaps on the other lane and accomplishing the maneuver in the most energy efficient way.

- *Does the information forwarded by the service foster smoother decelerations while the HC vehicle approaches an unavoidable spillage?*

If the unidentified liquid hinders the whole carriageway, the approaching vehicle should lower its speed values (both if the automation remains engaged or if the human driver takes back control). This deceleration can be smoother if the information is forwarded in advance, avoiding harsh braking and, thus, promoting a more energy efficient driving regime.

- *Does the information forwarded in advance make the take-over maneuvers smoother, avoiding harsh braking performed by the human driver?*

If the take-over maneuver is triggered in advance by the C-ITS message, the urgency of the maneuver itself should be lower, granting the human driver with enough time to resume a sufficient level of situational awareness and avoid both swerving and harsh braking, thus promoting a more energy efficient driving regime.

Assessment instrument

Assessing the environmental impacts should be accomplished mainly through field tests. The baseline scenario should consider HC vehicles unequipped for the cooperative message reception or informed only through VMS. The implementation scenario of the C-ITS service should be accurately defined, listing the operational parameters as communication ranges, the means of broadcasting and the information transmitted. Examples of this kind of specifications can be found in the dedicated C-Roads documents [71].

4.3.3.4. User Acceptance

Research question: How does the human driver perceive take-over maneuvers performed with adverse weather conditions?

The take-over transition can be perceived as unsafe or risky, especially in the short time and by unexperienced drivers. This can be especially true if the maneuver is performed with hindered visibility conditions while the human driver is re-assessing its situational awareness, which

means that knowing in advance about the adverse weather conditions and re-engaging the driving task before reaching the hazardous location can improve both the feeling of safety and acceptance towards the Highway Chauffeur system. Moreover, knowing that the system is aware of the adverse weather, thanks to the C-ITS service, and didn't issue a take-over request should foster a feeling of safety and trust even if the HC vehicle keeps driving in automated mode through, for example, light rain.

- *Did the driver perceived an increased usefulness both in the Highway Chauffeur system and in the C-ITS service, while re-engaging the driving task before reaching the adverse weather condition?*

Perceiving that the Highway Chauffeur system receives information about the weather conditions in advance should foster, in the human driver, a feeling of trust and safety both if the HC vehicle keeps driving in automated mode and during the take-over maneuver which should start enough time in advance for him or her to re-assess an acceptable level of situational awareness.

Assessment instrument

To assess User Acceptance, the most efficient tools are Surveys presented after field tests and large-scale demonstrations. Besides, it should be evaluated what information is broadcasted by the C-ITS, what is displayed on the HMI and the number of false positive or false negative that could arise from the use that the Highway Chauffeur makes of the weather-related information to issue the take-over maneuver or not.

Survey's Outputs

The following indicators should be collected after surveys:

- Situation awareness
- Knowledge about the Highway Chauffeur system and its capabilities
- Perceived comfort during the maneuvers carried out by the HC vehicle, while passing the hazardous location
- Perceived usefulness of the information broadcasted by the service, related to the utility for the Highway Chauffeur system
- Propensity to let the Highway Chauffeur system keep driving in automated mode through an adverse weather condition

- Number of false positives and false negatives related to the take-over maneuver before an adverse weather condition

Appendix

A.1. Highway Chauffeur

A.1.1. Traffic Efficiency

Data requirements – route parameters – design choices

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

- Speed – source: Can Bus data or GPS data
- ACC pre - set parameters – source: Can Bus data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- TTC or similar metrics during the lane changing maneuvers – source: Sensors data
- Traffic density – source: on-road detectors or through modeling works
- System ODD – source: by design
- Steering angle/action – source: Can Bus data

Field Test Indicators – Modeling Outputs

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

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation - source: Can Bus data or GPS data
- Instantaneous accelerations and decelerations – source: Can Bus data
- ACC parameters chosen by the human driver – source: Can Bus data
- Number of lane changing maneuvers interrupted – source: Can Bus data or GPS data
- Maximum jerk (rate of change in acceleration, longitudinal and lateral) – source: Can Bus data
- Other lane Average Speed and Average Gap chosen by the Highway Chauffeur system for the lane changing maneuvers
- Ratio between number of instances where the driver must take manual control and km driven – source: Can Bus data
- Time gap Accuracy/Stability – source: Can Bus data and/or equipped Sensors
- Take over triggers – source: Can Bus data
- Take-over mean time – source: Can Bus data

- Take-over maximum time – source: Can Bus data
- Maximum steering angle/action – source: Can Bus data
- Maximum braking action reached during a take-over maneuver – source: Can Bus data
- Traffic throughput through a particular road section – source: on-road detectors or through modeling to evaluate the implemented traffic control strategies
- % of the travelled kilometres driven with the Highway Chauffeur engaged – source: Can Bus data

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

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

- Change in Traffic Flow
- Change in Journey Time
- Change in Total Time spent by all vehicles in queue
- Change in queue length
- Change in Bottleneck Congestion
- Change in Road Capacity
- Change in VMT (Vehicle Miles Travelled)
- Change in commuters’ journeys and in perceived travel costs

Besides, an increased number of vehicles equipped to receive and sent CANM should strongly increase the reliability and availableness of real-time information, usable by road operators and Traffic Control Centres to implement more effective traffic control strategies.

Overview of the research questions

Traffic Efficiency - Data Requirements; Route Parameters; Design choices	How conservative is the automated system?	Does the longitudinal control law take into account strategies aimed at enhancing the traffic flow?	Does the Traffic Jam Chauffeur ease the traffic congestion, promoting an earlier return to the decongested state?
Speed	X	X	X

Traffic Efficiency - Data Requirements; Route Parameters; Design choices	How conservative is the automated system?	Does the longitudinal control law take into account strategies aimed at enhancing the traffic flow?	Does the Traffic Jam Chauffeur ease the traffic congestion, promoting an earlier return to the decongested state?
Acceleration Deceleration	X	X	X
ACC pre-set parameters		X	
Position		X	
TTC during lane changing maneuvers		X	
Steering angle/action		X	
Traffic Density		X	
System ODD		X	

Traffic Efficiency - Field Test Indicators and Modeling Outputs	How conservative is the automated system?	Does the longitudinal control law take into account strategies aimed at enhancing the traffic flow?	Does the Traffic Jam Chauffeur ease the traffic congestion, promoting an earlier return to the decongested state?	
Average Speed	X	X	X	
Speed Standard Deviation		X		
Instantaneous Acceleration/Deceleration		X		X
ACC parameters chosen by the human driver		X		X
Other lane average speed/average gap chosen by the HC system for the lane change		X		
Maximum jerk		X		X
Take-over requests/driven km		X		
Time Gap Accuracy/Stability				X
Take-over triggers		X		

Traffic Efficiency - Field Test Indicators and Modeling Outputs	How conservative is the automated system?	Does the longitudinal control law take into account strategies aimed at enhancing the traffic flow?	Does the Traffic Jam Chauffeur ease the traffic congestion, promoting an earlier return to the decongested state?
Take-over mean and maximum time	X	X	X
Maximum braking action during a take-over maneuver			
Maximum steering angle/action			
Traffic throughput through a road section			
Km driven with the system engaged/Km driven			

A.1.2. Safety

Data requirements – route parameters – design choices

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

- Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration or Brake pressure profile – source: Can Bus data or GPS data
- Position – source: GPS data
- ACC pre-set parameters – source: Can Bus data
- Steering angle – source: Can Bus data
- Time To Collision (TTC) – source: Sensors data

- Brake Threat Number (BTN) – source: Sensors data
- Percent Road Centre [42] or other gaze behavioural metrics [64] – source: eye tracking camera
- Warning delivery strategy: Visual, auditory, haptic or a combination of the above – source: by design
- System ODD – source: by design
- Type of interface: mobile phone, integrated HMI or others – source: by design
- Planned take-over time – source: by design

Field Test Indicators – Modeling Outputs

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

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data or GPS data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Lane position standard deviation – source: Can Bus data or cameras
- Time gap Accuracy/Stability – source: Can Bus data and/or equipped Sensors
- Minimum TTC (or similar metrics) reached – source: Sensors data
- Number of events involving safety-critical values of TTC or similar metrics – source: Sensors data
- Number of Cut-ins/Km for each time gap value considered – source: Cameras or Sensors data
- Maximum steering angle/action – source: Can Bus data
- Ratio between number of instances where the driver must take manual control and km driven – source: Can Bus data
- Number of emergency decelerations per km or miles – source: Can Bus data
- Mean take-over time – source: Can Bus data
- Maximum take-over time – source: Can Bus data
- Minimum time interval available for the take-over maneuver – source: GPS data or Can Bus data
- Secondary task engaged by the driver – source: internal cameras
- Maximum duration of the glances off-road – source: internal cameras
- Other lane average time gap chosen by the HC system for the lane changing maneuvers – source: Can Bus data

- TTC and BTN values during a cut-in from an external vehicle – source: Can Bus data or cameras
- Maximum braking value reached during a take-over maneuver – source: Can Bus data
- Number of false positives while issuing the take-over request
- % of the travelled kilometres driven with the Highway Chauffeur engaged – source: Can Bus data

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

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

- Change in number of accidents, fatalities and injuries
- Arising of new type of accidents bound to the automation and its relationship with the human drivers
- Change in number of involved drivers
- Skill degradation

Overview of the research questions

Safety - Data Requirements; Route Parameters; Design choices	Can the maneuvers performed by the HC vehicles and their interaction with other road users lead to dangerous scenarios?	In case of safety-critical scenarios, is the fall-back strategy of the HC vehicle able to avoid collisions?	Does the transition in control happen in a safe and reliable way?
Speed	X	X	X
Acceleration/Deceleration	X	X	X
Position	X	X	X

Safety - Data Requirements; Route Parameters; Design choices	Can the maneuvers performed by the HC vehicles and their interaction with other road users lead to dangerous scenarios?	In case of safety-critical scenarios, is the fall-back strategy of the HC vehicle able to avoid collisions?	Does the transition in control happen in a safe and reliable way?
TTC or similar metrics	X	X	X
Percent Road Centre		X	
Steering angle		X	
Warning delivery strategy		X	
Type of interface		X	
Planned Take-over time		X	
System ODD		X	

Safety - Field Test Indicators and Modeling Outputs	Can the maneuvers performed by the HC vehicles and their interaction with other road users lead to dangerous scenarios?	In case of safety-critical scenarios, is the fall-back strategy of the HC vehicle able to avoid collisions?	Does the transition in control happen in a safe and reliable way?
Average Speed	X	X	X
Speed Standard Deviation	X	X	X
Instantaneous Acceleration/Deceleration	X	X	X
Lane position standard deviation	X	X	X
Time Gap Accuracy/Stability	X		
Minimum TTC (or similar metrics) reached	X	X	X
Number of events involving safety-critical values of TTC or similar metrics	X	X	
Number of Cut-ins/Km for each time gap value considered	X		
TTC (or similar metrics) value during a cut-in	X		
Time Gap chosen by the HC system for the lane changing maneuver	X		

Safety - Field Test Indicators and Modeling Outputs	Can the maneuvers performed by the HC vehicles and their interaction with other road users lead to dangerous scenarios?	In case of safety-critical scenarios, is the fall-back strategy of the HC vehicle able to avoid collisions?	Does the transition in control happen in a safe and reliable way?	
Maximum steering angle	X	X	X	
Mean take-over time		X		
Maximum take-over time		X		
Minimum time available for the take-over transition		X		
Maximum duration of the glances off-road		X		
Maximum braking value reached during a take-over request		X		
Number of instances where the driver must take manual control/Km driven		X		
Number of false positives while issuing the take-over request		X		
Number of emergency braking/km driven		X		X
% of travelled kilometres driven with the Highway Chauffeur system engaged		X		X

A.1.3. Environment

Data requirements – route parameters – design choices

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

- Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration or Brake pedal pressure – source: Can Bus data or GPS data
- Steering angle – source: Can Bus data
- Position – source: GPS data
- ACC pre-set parameters – source: ACC system or Can Bus data
- Fuel consumption – source: Can Bus data
- System ODD – source: by design

Field Test Indicators – Modeling outputs

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

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Maximum steering angle – source: Can Bus data
- Other lane average speed/average gap chosen by the HC system for the lane change - source: Can Bus data
- Number of take-over maneuvers per kilometre – source: Can Bus data
- Maximum braking action reached during a take-over maneuver – source: Can Bus data
- Travel time – source: GPS data
- Fuel consumption – source: Can Bus data
- Noise level – source: based on speed and on the aggressiveness of the driving regime [96]
- Queue length during a traffic jam – source: on-road detectors
- % of the travelled kilometres driven with the Highway Chauffeur engaged – source: Can Bus data

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

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

- Change in Traffic Flow
- Change in Journey Time
- Change in queue length
- Change in Bottleneck Congestion
- Change in Total Time spent by all vehicles in queue
- Change in Road Capacity
- Change in vehicles weight
- Change in traffic CO₂ or polluting emissions
- Change in noise pollution
- Change in fuel consumption
- Modal shift from more environmental-friendly transport systems (such as railway) to the road system
- Change in Vehicle Miles Travelled

Overview of the sub-research questions

Environment - Data Requirements; Route Parameters; Design choices	Does a more efficient longitudinal control foster a decrease in fuel consumption?	Do traffic management strategies that exploit the presence of automated vehicles prevent or reduce congestion??	Do the maneuvers carried out by the HC vehicle have a reduced impact on the surrounding traffic?	Does the Traffic Jam Chauffeur foster a more efficient Stop&Go driving?	Is the take-over maneuver carried out in a smooth?	Does the HC driving style synergize with the electric vehicle's technology, assuring a more energy-efficient driving behaviour?	Is a driver out of the driving loop encouraged to let the HC vehicle choose the most energy efficient route, even if a little bit longer?
Speed	X	X	X		X	X	X
Acceleration Deceleration	X		X	X	X	X	X
Steering angle			X		X		

Environment - Data Requirements; Route Parameters; Design choices	Does a more efficient longitudinal control foster a decrease in fuel consumption?	Do traffic management strategies that exploit the presence of automated vehicles prevent or reduce congestion??	Do the maneuvers carried out by the HC vehicle have a reduced impact on the surrounding traffic?	Does the Traffic Jam Chauffeur foster a more efficient Stop&Go driving?	Is the take-over maneuver carried out in a smooth?	Does the HC driving style synergize with the electric vehicle's technology, assuring a more energy-efficient driving behaviour?	Is a driver out of the driving loop encouraged to let the HC vehicle choose the most energy efficient route, even if a little bit longer?
Position	X	X	X	X			X
ACC pre-set parameters	X	X		X			
Fuel consumption	X	X	X	X	X	X	X
System ODD	X		X		X		X

Environment – Field test indicators and modeling outputs	Does a more efficient longitudinal control foster a decrease in fuel consumption?	Do traffic management strategies that exploit the presence of automated vehicles prevent or reduce congestion??	Do the maneuvers carried out by the HC vehicle have a reduced impact on the surrounding traffic?	Does the Traffic Jam Chauffeur foster a more efficient Stop&Go driving?	Is the take-over maneuver carried out in a smooth?	Does the HC driving style synergize with the electric vehicle's technology, assuring a more energy-efficient driving behaviour?	Is a driver out of the driving loop encouraged to let the HC vehicle choose the most energy efficient route, even if a little bit longer?
Average Speed	X	X	X			X	X

Environment – Field test indicators and modeling outputs	Does a more efficient longitudinal control foster a decrease in fuel consumption?	Do traffic management strategies that exploit the presence of automated vehicles prevent or reduce congestion??	Do the maneuvers carried out by the HC vehicle have a reduced impact on the surrounding traffic?	Does the Traffic Jam Chauffeur foster a more efficient Stop&Go driving?	Is the take-over maneuver carried out in a smooth?	Does the HC driving style synergize with the electric vehicle's technology, assuring a more energy-efficient driving behaviour?	Is a driver out of the driving loop encouraged to let the HC vehicle choose the most energy efficient route, even if a little bit longer?
Speed Standard Deviation	X		X	X	X	X	
Instantaneous accelerations and decelerations	X		X	X	X	X	
Maximum steering angle			X		X		
Time Gap chosen by the HC system for the lane changing maneuver			X				
Number of take-over maneuvers per kilometer					X		X
Maximum braking action during a take-over maneuver	X				X		
Queue length during a Traffic Jam		X		X			

Environment – Field test indicators and modeling outputs	Does a more efficient longitudinal control foster a decrease in fuel consumption?	Do traffic management strategies that exploit the presence of automated vehicles prevent or reduce congestion??	Do the maneuvers carried out by the HC vehicle have a reduced impact on the surrounding traffic?	Does the Traffic Jam Chauffeur foster a more efficient Stop&Go driving?	Is the take-over maneuver carried out in a smooth?	Does the HC driving style synergize with the electric vehicle’s technology, assuring a more energy-efficient driving behaviour?	Is a driver out of the driving loop encouraged to let the HC vehicle choose the most energy efficient route, even if a little bit longer?				
Travel Time	X	X	X	X	X	X	X				
Fuel consumption							X	X	X	X	X
Noise level							X	X	X	X	X
% of travelled kilometres driven with the HC system engaged							X	X	X	X	X

A.1.4. Overall and User Acceptance

Field test Indicators and Survey’s Outputs

The following indicators should be collected after surveys:

- Situational awareness
- Knowledge about the Highway Chauffeur system
- Problem perception related to each maneuver
- Preferences about the driving style and the ACC parameters
- Preferences about the HMI design and support
- Preferences about the means of warning
- Perceived threat level – feeling of safety
- Number of interrupted maneuvers

- Number of take-over requests
- Relationship with the HMI
- Wearable garments parameters

A.2. Jointed impacts of Highway Chauffeur and C-ITS

A.2.1. Road Works Warning – Closure of part of a lane, whole lane or several lanes

Traffic Efficiency

Data requirements – route parameters – design choices

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

- Message sent and received/Message content – Data logs
- Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- Lateral position standard deviation – source: Cameras
- Steering angle – source: Can Bus data
- ACC pre-set parameters – source: ACC system and Can Bus data
- System ODD – source: by design
- TTC or similar metrics – source: Sensors data

Field Test Indicators – Modeling outputs

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

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Reception point of the C-ITS message – Can Bus data and GPS data
- Lane change point – source: Can Bus data or GPS data
- Maximum jerk (rate of change in acceleration, longitudinal and lateral) – source: Can Bus data
- Other lane average speed/average gap chosen by the HC system for the lane change – source: Can Bus data

- Traffic densities beyond which the lane changing maneuver is hindered – source: on-road detectors and Can Bus data or through modeling works
- Average flow across the bottleneck section – source: on-road detectors or through modeling works
- Dynamic capacity (i.e., the downstream outflow from traffic congestion) – source: on-road detectors or through modeling works
- Kept time gaps (set by the human driver or suggested by the C-ITS) – source: Can Bus data
- Number of roadworks encountered that fell off the system ODD (and the causing factors such as light and weather conditions, improper signalling, etc.) – source: Can Bus data
- Number of instances where the driver must take manual control – source: Can Bus data
- Take over triggers – source: Can Bus data
- Take-over mean time – source: Can Bus data
- Take-over maximum time – source: Can Bus data
- Time gap Accuracy/Stability – source: Can Bus data and/or equipped Sensors
- Maximum steering angle/action – source: Can Bus data
- Maximum braking action reached during a take-over maneuver – source: Can Bus data
- Minimum distance from lateral boundaries – source: Cameras
- Minimum TTC or similar metrics – source: Sensors data
- Number of events involving safety-critical values of TTC or similar metrics – source: Sensors data
- Lateral Position Standard Deviation – source: Cameras

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

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

- Change in Traffic Flow
- Change in Journey Time
- Change in Bottleneck Congestion
- Change in Total Time spent by all vehicles in queue
- Change in commuters' journeys and in perceived travel costs

Overview of the sub-research questions

Traffic Efficiency – Data requirements; Route parameters; Design choices	Does the information forwarded in advance allow the Highway Chauffeur system to remain engaged through the roadworks?	Is the HC vehicle’s lane changing maneuver smoother thanks to the received information?	Does the HC vehicle adapt its speed earlier and in a more efficient way thanks to the forwarded information?	Does the Traffic Jam Chauffeur function ease the bottleneck congestion? Do increased time gaps worsen the bottleneck congestion, instead?	Does an earlier take-over request diminish the number of sudden braking performed by the human driver?	Does an earlier take-over request help the human driver perform a more efficient lane changing maneuver?	Do an earlier take-over request and the information delivered by the C-ITS improve the situational awareness of the human driver and the efficiency of his driving?	Does the C-ITS make a partial degradation in the automation level possible or easier?
Message sent and received – Message content	X	X	X		X	X	X	X
Speed	X		X	X			X	X
Acceleration Deceleration	X	X	X	X	X	X	X	X
Position	X	X	X	X	X	X	X	X
Lateral position standard deviation	X	X				X	X	X

Traffic Efficiency – Data requirements; Route parameters; Design choices	Does the information forwarded in advance allow the Highway Chauffeur system to remain engaged through the roadworks?	Is the HC vehicle’s lane changing maneuver smoother thanks to the received information?	Does the HC vehicle adapt its speed earlier and in a more efficient way thanks to the forwarded information?	Does the Traffic Jam Chauffeur function ease the bottleneck congestion? Do increased time gaps worsen the bottleneck congestion, instead?	Does an earlier take-over request diminish the number of sudden braking performed by the human driver?	Does an earlier take-over request help the human driver perform a more efficient lane changing maneuver?	Do an earlier take-over request and the information delivered by the C-ITS improve the situational awareness of the human driver and the efficiency of his driving?	Does the C-ITS make a partial degradation in the automation level possible or easier?
Steering angle	X	X				X	X	X
ACC pre-set parameters				X				
TTC or similar metrics	X	X		X	X	X	X	

Traffic Efficiency – Field tests indicators and modeling outputs	Does the information forwarded in advance allow the Highway Chauffeur system to remain engaged through the roadworks?	Is the HC vehicle’s lane changing maneuver smoother thanks to the received information?	Does the HC vehicle adapt its speed earlier and in a more efficient way thanks to the forwarded information?	Does the Traffic Jam Chauffeur function ease the bottleneck congestion? Do increased time gaps worsen the bottleneck congestion, instead?	Does an earlier take-over request diminish the number of sudden braking performed by the human driver?	Does an earlier take-over request help the human driver perform a more efficient lane changing maneuver?	Do an earlier take-over request and the information delivered by the C-ITS improve the situational awareness of the human driver and the efficiency of his driving?	Does the C-ITS make a partial degradation in the automation level possible or easier?
Average Speed	X		X			X	X	
Speed Standard Deviation	X	X	X	X	X	X	X	X

Traffic Efficiency – Field tests indicators and modeling outputs	Does the information forwarded in advance allow the Highway Chauffeur system to remain engaged through the roadworks?	Is the HC vehicle's lane changing maneuver smoother thanks to the received information?	Does the HC vehicle adapt its speed earlier and in a more efficient way thanks to the forwarded information?	Does the Traffic Jam Chauffeur function ease the bottleneck congestion? Do increased time gaps worsen the bottleneck congestion, instead?	Does an earlier take-over request diminish the number of sudden braking performed by the human driver?	Does an earlier take-over request help the human driver perform a more efficient lane changing maneuver?	Do an earlier take-over request and the information delivered by the C-ITS improve the situational awareness of the human driver and the efficiency of his driving?	Does the C-ITS make a partial degradation in the automation level possible or easier?
Instantaneous acceleration and deceleration	X	X	X	X	X	X	X	X
Reception point	X	X	X		X	X	X	X
Lane change point	X	X				X		
Maximum steering angle	X	X				X		
Maximum jerk	X	X	X	X	X	X	X	X
Other lane average gap chosen by the HC system for the lane changing maneuver	X	X				X		
Other lane average speed chosen by the HC system for the lane changing maneuver	X	X				X		

Traffic Efficiency – Field tests indicators and modeling outputs	Does the information forwarded in advance allow the Highway Chauffeur system to remain engaged through the roadworks?	Is the HC vehicle's lane changing maneuver smoother thanks to the received information?	Does the HC vehicle adapt its speed earlier and in a more efficient way thanks to the forwarded information?	Does the Traffic Jam Chauffeur function ease the bottleneck congestion? Do increased time gaps worsen the bottleneck congestion, instead?	Does an earlier take-over request diminish the number of sudden braking performed by the human driver?	Does an earlier take-over request help the human driver perform a more efficient lane changing maneuver?	Do an earlier take-over request and the information delivered by the C-ITS improve the situational awareness of the human driver and the efficiency of his driving?	Does the C-ITS make a partial degradation in the automation level possible or easier?
Traffic densities beyond which the lane changing maneuver is hindered	X	X				X		
Average flow across the bottleneck section	X	X	X	X		X	X	
Dynamic capacity	X	X	X	X		X	X	
Kept time gaps				X				
Number of Roadworks encountered that fell off the system ODD	X	X	X	X				X
Number of instances where the driver must take manual control					X	X	X	X
Take-over triggers					X	X	X	X

Traffic Efficiency – Field tests indicators and modeling outputs	Does the information forwarded in advance allow the Highway Chauffeur system to remain engaged through the roadworks?	Is the HC vehicle's lane changing maneuver smoother thanks to the received information?	Does the HC vehicle adapt its speed earlier and in a more efficient way thanks to the forwarded information?	Does the Traffic Jam Chauffeur function ease the bottleneck congestion? Do increased time gaps worsen the bottleneck congestion, instead?	Does an earlier take-over request diminish the number of sudden braking performed by the human driver?	Does an earlier take-over request help the human driver perform a more efficient lane changing maneuver?	Do an earlier take-over request and the information delivered by the C-ITS improve the situational awareness of the human driver and the efficiency of his driving?	Does the C-ITS make a partial degradation in the automation level possible or easier?
Take-over mean time	X				X	X	X	X
Take-over maximum time					X	X	X	X
Maximum braking action reached during a take-over maneuver						X	X	
Time Gap accuracy - stability				X	X			
Minimum TTC or similar metrics reached			X	X	X	X	X	X
Number of events involving safety critical values of TTC			X	X	X	X	X	X
Minimum distance from lateral boundaries reached							X	X

Safety

Data requirements – route parameters – design choices

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

- Message sent and received/Message content – Data logs
- Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Steering angle – source: Can Bus data
- TTC or equivalent metrics – source: Sensors data
- Warning delivery strategy: Visual, auditory, haptic or a combination of the above – source: by design
- System ODD – source: by design

Field Test Indicators – Modeling outputs

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

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Reception point of the C-ITS message – Can Bus data and GPS data
- Lane change point – source: Can Bus data or GPS data
- Other lane average speed/average gap chosen by the HC system for the lane change – source: Can Bus data
- Minimum TTC or similar metrics – source: sensors data
- Number of events involving safety-critical values of TTC or similar metrics – source: sensors data
- Lateral Position Standard Deviation – source: Sensors data
- Time gap Accuracy/Stability – source: Can Bus data and/or equipped Sensors
- Number of emergency braking per km or miles – source: Can Bus data

Overview of the sub-research questions

Safety – Data requirements; Route parameters; Design choices	Is the HC vehicle’s lane changing maneuver smoother thanks to the received information?	Does the HC vehicle adapt its speed while approaching the work zone in a smoother and safer way?	Does the number pre-crash scenarios lower thanks to the information granted by the C-ITS?	Does the information delivered by the C-ITS widen the system ODD, avoiding take-over maneuvers?	Is the take-over maneuver carried out in a smoother way?	Does the driver achieve an acceptable level of situational awareness before performing the lane changing maneuver?
Message sent and received – Message content	X	X	X	X	X	X
Speed	X	X	X		X	
Acceleration Deceleration	X	X	X	X	X	X
Steering angle	X		X		X	X
TTC or equivalent metric	X	X	X		X	X
Warning delivery strategy			X		X	X
System ODD	X	X	X	X	X	X

Safety – Field test indicators and modeling outputs	Is the HC vehicle's lane changing maneuver smoother thanks to the received information?	Does the HC vehicle adapt its speed while approaching the work zone in a smoother and safer way?	Does the number pre-crash scenarios lower thanks to the information granted by the C-ITS?	Does the information delivered by the C-ITS widen the system ODD, avoiding take-over maneuvers?	Is the take-over maneuver carried out in a smoother way?	Does the driver achieve an acceptable level of situational awareness before performing the lane changing maneuver?
Average Speed		X	X		X	
Speed Standard Deviation		X	X	X	X	X
Instantaneous accelerations and decelerations	X	X	X		X	
Reception point	X	X	X	X	X	X
Lane change point	X			X		X
Time Gap accuracy - stability			X	X		
Average speed on the other lane chosen by the HC system for the lane changing maneuver	X		X	X		

Safety – Field test indicators and modeling outputs	Is the HC vehicle's lane changing maneuver smoother thanks to the received information?	Does the HC vehicle adapt its speed while approaching the work zone in a smoother and safer way?	Does the number pre-crash scenarios lower thanks to the information granted by the C-ITS?	Does the information delivered by the C-ITS widen the system ODD, avoiding take-over maneuvers?	Is the take-over maneuver carried out in a smoother way?	Does the driver achieve an acceptable level of situational awareness before performing the lane changing maneuver?
Average gap on the other lane chosen by the HC system for the lane changing maneuver	X		X	X		
Minimum TTC or similar metrics	X	X	X	X	X	X
Number of events involving safety-critical values of TTC/km driven	X	X	X	X	X	X
Lateral position standard deviation			X	X	X	X
Number of emergency braking per km or miles	X	X	X		X	X

Environment

Data requirements – route parameters – design choices

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

- Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- Message sent and received/Message content – Data logs

- ACC parameters – source: ACC system and Can Bus data
- Steering angle – source: Can Bus data
- Fuel consumption – source: Can Bus data
- System ODD – source: by design

Field Test Indicators – Modeling outputs

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

- Average Speed – source: Can Bus data or GPS data
 - Speed Standard Deviation – source: Can Bus data
 - Instantaneous accelerations and decelerations – source: Can Bus data
 - Reception point of the C-ITS message – source: GPS data and Can Bus data
 - Lane change point – source: Can Bus data or GPS data
 - Maximum steering angle – source: Can Bus data
 - Maximum jerk (rate of change in acceleration, longitudinal and lateral) – source: Can Bus data
 - Other lane average speed/average gap chosen by the HC system for the lane change – source: Can Bus data
 - Number of instances where the driver must take manual control – source: Can Bus data
 - Maximum braking value reached during a take-over request – source: Can Bus data
 - Traffic densities beyond which the lane changing maneuver is hindered – source: on-road detectors and Can Bus data or through modeling works
 - Average flow across the bottleneck section – source: on-road detectors or modeling works
 - Fuel consumption – source: Can Bus data
 - Noise level – source: based on speed and on the aggressiveness of the driving regime
- [96]

Overview of the sub-research questions

Environment – Data requirements; Route parameters; Design choices	Does the service allow a greater number of HC vehicles to keep driving without issuing a take-over request?	Do the smoother lane changes have an impact on the surrounding traffic flow and on shockwaves creation and propagation?	Does the Traffic Jam Chauffeur function ease the bottleneck congestion? Do increased time gaps worsen the bottleneck congestion, instead?
Message sent and received – Message content	X	X	X
Speed		X	
Acceleration Deceleration		X	
Steering angle		X	
ACC pre-set parameters		X	
Fuel consumption	X	X	X
System ODD	X	X	X

Environment – Field Test Indicators and modeling outputs	Does the service allow a greater number of HC vehicles to keep driving without issuing a take-over request?	Do the smoother lane changes have an impact on the surrounding traffic flow and on shockwaves creation and propagation?	Does the Traffic Jam Chauffeur function ease the bottleneck congestion? Do increased time gaps worsen the bottleneck congestion, instead?	
Average Speed		X	X	
Speed Standard Deviation		X	X	
Instantaneous accelerations and decelerations		X	X	X
Reception point		X	X	X
Lane change point		X	X	
Maximum steering angle		X	X	
Maximum jerk		X	X	X

Environment – Field Test Indicators and modeling outputs	Does the service allow a greater number of HC vehicles to keep driving without issuing a take-over request?	Do the smoother lane changes have an impact on the surrounding traffic flow and on shockwaves creation and propagation?	Does the Traffic Jam Chauffeur function ease the bottleneck congestion? Do increased time gaps worsen the bottleneck congestion, instead?
Other lane average speed/average gap chosen by the HC system for the lane change	X	X	X
Traffic densities beyond which the lane changing maneuver is hindered			
Number of instances where the driver must take back manual control			
Maximum braking value reached during a take-over request			
Average flow across the bottleneck section			
Fuel consumption			
Noise level			

User Acceptance

Survey's Outputs

The following indicators should be collected after surveys:

- Situation awareness
- Knowledge about the Highway Chauffeur system and its capabilities
- Problem perception related to the approached roadworks
- Perceived threats for the driver himself or for the workers on the road

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

Traffic Efficiency

Data requirements – route parameters – design choices

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

- Message sent and received/Message content – Data logs
- Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- ACC pre-set parameters – source: ACC system and Can Bus data
- System ODD – source: by design

Field Test Indicators – Modeling outputs

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

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Reception point of the C-ITS message – Can Bus data and GPS data
- Maximum jerk (rate of change in acceleration, longitudinal and lateral) – source: Can Bus data
- Average flow across the bottleneck section – source: on-road detectors or through modeling works
- Dynamic capacity (i.e., the downstream outflow from traffic congestion) – source: on-road detectors or through modeling works

- Adopted time gaps (set by the human driver or suggested by the C-ITS) – source: ACC system and Can Bus data

Overview of the sub-research questions

Traffic Efficiency – Data requirements; Route parameters; Design choices	Is the HC vehicle’s speed more compliant with the suggested speed limit?	How do the instant speed fluctuations change?	Does delaying the arrival of HC vehicle to the congested section actually improve the overall traffic efficiency?	How does having ACC- equipped vehicles upstream the queue impact on the congestion recovery?
Message sent and received – Message content	X	X	X	X
Speed	X		X	X
Acceleration Deceleration	X	X	X	X
Position	X	X	X	X
ACC pre-set parameters	X			X
System ODD	X	X	X	X

Traffic Efficiency – Field test indicators and modeling outputs	Is the HC vehicle’s speed more compliant with the suggested speed limit?	How do the instant speed fluctuations change?	Does delaying the arrival of HC vehicle to the congested section actually improve the overall traffic efficiency?	How does having ACC-equipped vehicles upstream the queue impact on the congestion recovery?
Average Speed	X	X	X	X
Speed Standard Deviation		X		X
Instantaneous accelerations and decelerations		X		X
Reception point	X	X	X	X
Maximum jerk		X		X
Average flow across the bottleneck section	X	X	X	X
Dynamic capacity	X	X	X	X

Traffic Efficiency – Field test indicators and modeling outputs	Is the HC vehicle’s speed more compliant with the suggested speed limit?	How do the instant speed fluctuations change?	Does delaying the arrival of HC vehicle to the congested section actually improve the overall traffic efficiency?	How does having ACC-equipped vehicles upstream the queue impact on the congestion recovery?
Adopted time gaps				X

Environment

Data requirements – route parameters – design choices

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

- Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- Message sent and received/Message content – Data logs
- ACC pre-set parameters – source: ACC system and Can Bus data
- Market penetration of ACC-equipped vehicles among the traffic flow
- Fuel consumption – source: Can Bus data

Field Test Indicators – Modeling outputs

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

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Reception point – source: GPS data and Can Bus data
- Speed adaptation (difference between the average speed of the vehicle and the speed limit) from the reception of the C-ITS message until the suggested speed limit is no longer relevant – source: Can Bus data or GPS data

- Maximum jerk (rate of change in acceleration, longitudinal and lateral) – source: Can Bus data
- Average flow across the bottleneck section – source: on-road detectors or through modeling
- Queue length – source: on-road detectors or through modeling
- Fuel consumption – source: Can Bus data
- Noise level – source: based on speed and on the aggressiveness of the driving regime [96]

Overview of the sub-research questions

Environment – Data requirements; Route parameters; Design choices	How do the instant speed fluctuations change?	Do the informed HC vehicles actually avoid getting stuck in traffic jams?	How does having ACC-equipped vehicles upstream the queue impact on the congestion recovery?
Message sent and received – Message content	X	X	X
Speed		X	X
Acceleration Deceleration	X	X	X
Position	X	X	X

Environment – Data requirements; Route parameters; Design choices	How do the instant speed fluctuations change?	Do the informed HC vehicles actually avoid getting stuck in traffic jams?	How does having ACC-equipped vehicles upstream the queue impact on the congestion recovery?
ACC pre-set parameters			X
Market penetration of ACC-equipped vehicles among the traffic flow			X
Fuel consumption			X

Environment – Field test indicators and modeling outputs	How do the instant speed fluctuations change?	Do the informed HC vehicles actually avoid getting stuck in traffic jams?	How does having ACC-equipped vehicles upstream the queue impact on the congestion recovery?
Average Speed		X	X
Speed Standard Deviation		X	X

Environment – Field test indicators and modeling outputs	How do the instant speed fluctuations change?	Do the informed HC vehicles actually avoid getting stuck in traffic jams?	How does having ACC-equipped vehicles upstream the queue impact on the congestion recovery?
Instantaneous accelerations and decelerations	X	X	X
Reception point			
Speed adaptation			
Maximum jerk			
Average flow across the bottleneck section			
Queue length			
Fuel consumption			

Environment – Field test indicators and modeling outputs	How do the instant speed fluctuations change?	Do the informed HC vehicles actually avoid getting stuck in traffic jams?	How does having ACC-equipped vehicles upstream the queue impact on the congestion recovery?
Noise level	X	X	X

User Acceptance

Survey's Outputs

The following indicators should be collected after surveys:

- Situation awareness
- Knowledge about the Highway Chauffeur system and its capabilities
- Knowledge about the Traffic Jam Chauffeur system and its capabilities
- Perception of the time spent in queue

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

Traffic Efficiency

Data requirements-route parameters-design choices

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

- Message sent and received/Message content – Data logs
- Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- Lateral position lane deviation – source: Cameras
- Steering angle – source: Can Bus data
- ACC pre-set parameters – source: ACC system and Can Bus data

- System ODD – source: by design
- Slow vehicle speed – source: cameras
- Number of lanes hindered by the event – source: Message data log
- Traffic Density – source: on-road detectors or through modeling works

Field Test Indicators – Modeling outputs

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

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Reception point of the C-ITS message – Can Bus data and GPS data
- Lane change point – source: Can Bus data or GPS data
- Maximum jerk (rate of change in acceleration, longitudinal and lateral) – source: Can Bus data
- Gap chosen for the lane changing maneuver – source: Can Bus data
- Traffic densities beyond which the lane changing maneuver is hindered – source: on-road detectors and Can Bus data or through modeling works
- Average flow across the bottleneck section – source: on-road detectors or through modeling works
- Dynamic capacity (i.e., the downstream outflow from traffic congestion) – source: on-road detectors or through modeling works
- Kept time gaps (set by the human driver or suggested by the C-ITS) – source: Can Bus data
- Travel time delay/ Time queued behind the accident zone or the broken down vehicle – source: GPS data

Overview of the sub-research questions

Traffic Efficiency – Data requirements; Route parameters; Design choices	How does the lane change point vary (if the lane of the event is specified)? Are the accomplished lane changing maneuvers smoother?	Does the average speed decrease?	If the slow or stationary vehicle is the source of the V2V message, does the HC vehicle perform a smoother braking while approaching the broken-down vehicle?
Message sent and received – Message content	X	X	X
Speed		X	
Acceleration Deceleration		X	
Position		X	
Steering angle		X	
Lateral position lane deviation		X	
ACC pre-set parameters			X

Traffic Efficiency – Data requirements; Route parameters; Design choices	How does the lane change point vary (if the lane of the event is specified)? Are the accomplished lane changing maneuvers smoother?	Does the average speed decrease?	If the slow or stationary vehicle is the source of the V2V message, does the HC vehicle perform a smoother braking while approaching the broken-down vehicle?
Slow vehicle speed	X	X	X
Number of lanes hindered by the event		X	
Traffic Density		X	
System ODD		X	

Traffic Efficiency – Field test parameters and modeling outputs	How does the lane change point vary (if the lane of the event is specified)? Are the accomplished lane changing maneuvers smoother?	Does the average speed decrease?	If the slow or stationary vehicle is the source of the V2V message, does the HC vehicle perform a smoother braking while approaching the broken-down vehicle?
Average Speed	X	X	X

Traffic Efficiency – Field test parameters and modeling outputs	How does the lane change point vary (if the lane of the event is specified)? Are the accomplished lane changing maneuvers smoother?	Does the average speed decrease?	If the slow or stationary vehicle is the source of the V2V message, does the HC vehicle perform a smoother braking while approaching the broken-down vehicle?
Speed Standard Deviation	X	X	X
Instantaneous accelerations and decelerations	X	X	X
Reception point	X	X	X
Lane change point	X		
Maximum jerk	X		X
Other lane average speed/average gap chosen by the HC system for the lane change	X		
Traffic density beyond which the lane changing maneuver is hindered	X		

Traffic Efficiency – Field test parameters and modeling outputs	How does the lane change point vary (if the lane of the event is specified)? Are the accomplished lane changing maneuvers smoother?	Does the average speed decrease?	If the slow or stationary vehicle is the source of the V2V message, does the HC vehicle perform a smoother braking while approaching the broken-down vehicle?
Average flow across the bottleneck section	X	X	X
Dynamic capacity	X	X	X
Kept time gaps	X		X
Travel time delay – Time queued behind the accident zone or the broken down vehicle	X	X	X

Safety

Data requirements – route parameters – design choices

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

- Message sent and received/Message content – Data logs
- Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- Steering angle – source: Can Bus data
- Warning delivery strategy: Visual, auditory, haptic or a combination of the above – source: by design
- Time to Collision or similar metrics – source: Sensors data

- System ODD – source: by design
- Slow vehicle speed – source: cameras
- Number of lanes hindered by the event – source: Message data log

Field Test Indicators – Modeling outputs

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

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Reception point of the C-ITS message – Can Bus data and GPS data
- Maximum jerk (rate of change in acceleration, longitudinal and lateral) – source: Can Bus data
- Lane change point – source: Can Bus data or GPS data
- Maximum steering angle – source: Can Bus data
- Overtaking/Lane change maneuver starting speed – source: Can Bus data
- Other lane average speed/average gap chosen by the HC system for the lane change – source: Can Bus data
- Traffic densities beyond which the lane changing maneuver is hindered – source: on-road detectors and Can Bus data or through modeling works
- Minimum TTC (or similar metrics) reached – source: Sensors data
- Number of events involving safety-critical values of TTC or similar metrics – source: Sensors data
- Lateral Position Standard Deviation – source: Can Bus data
- Number of emergency decelerations per km or miles – source: Can Bus data
- Number of instances where the driver must take manual control, triggered by the hazardous event – source: Can Bus data

Overview of the sub-research questions

Safety – Data requirements; Route parameters; Design choices	Does the number pre-crash scenarios lower thanks to the information granted by the C-ITS?	Does the information granted in advance prevent the HC vehicle from colliding with the signalized hindrance or with the surrounding vehicles (e.g. during an evasive maneuver)?	Does the HC vehicle adapt its speed to be more compliant with the suggested speed limit?	Is the take-over transition carried out in a smoother and safer way?
Message sent and received – Message content	X	X	X	X
Speed	X	X	X	X
Acceleration Deceleration	X			X
Position	X	X	X	X
Steering angle	X	X		X
Time to Collision or similar metrics	X	X		
Slow vehicle speed	X	X	X	

Safety – Data requirements; Route parameters; Design choices	Does the number pre-crash scenarios lower thanks to the information granted by the C-ITS?	Does the information granted in advance prevent the HC vehicle from colliding with the signalized hindrance or with the surrounding vehicles (e.g. during an evasive maneuver)?	Does the HC vehicle adapt its speed to be more compliant with the suggested speed limit?	Is the take-over transition carried out in a smoother and safer way?
Number of lanes hindered by the event	X	X		
Warning delivery strategy	X			X
System ODD	X	X		X

Safety – Field test indicators and modeling works	Does the number pre-crash scenarios lower thanks to the information granted by the C-ITS?	Does the information granted in advance prevent the HC vehicle from colliding with the signalized hindrance or with the surrounding vehicles (e.g. during an evasive maneuver)?	Does the HC vehicle adapt its speed to be more compliant with the suggested speed limit?	Is the take-over transition carried out in a smoother and safer way?
Average Speed	X	X	X	X
Speed Standard Deviation	X	X	X	X

Safety – Field test indicators and modeling works	Does the number pre-crash scenarios lower thanks to the information granted by the C-ITS?	Does the information granted in advance prevent the HC vehicle from colliding with the signaled hindrance or with the surrounding vehicles (e.g. during an evasive maneuver)?	Does the HC vehicle adapt its speed to be more compliant with the suggested speed limit?	Is the take-over transition carried out in a smoother and safer way?
Instantaneous acceleration and deceleration	X	X		X
Reception point	X	X	X	X
Maximum jerk	X	X	X	X
Lane change point	X	X		
Maximum steering angle	X	X		
Overtaking or lane changing maneuver starting speed	X	X	X	
Other lane average speed/average gap chosen by the HC system for the lane change	X	X		

Safety – Field test indicators and modeling works	Does the number pre-crash scenarios lower thanks to the information granted by the C-ITS?	Does the information granted in advance prevent the HC vehicle from colliding with the signaled hindrance or with the surrounding vehicles (e.g. during an evasive maneuver)?	Does the HC vehicle adapt its speed to be more compliant with the suggested speed limit?	Is the take-over transition carried out in a smoother and safer way?
Traffic density beyond which the lane change is hindered	X	X		X
Minimum TTC (or similar metrics) reached	X	X		X
Number of events involving safety-critical values of TTC or similar metrics	X	X		X
Lateral position standard deviation				X
Number of emergency braking/km driven	X			X
Number of instances where the driver must take manual control, triggered by the hazardous event	X	X		

Environment

Data requirements – route parameters – design choices

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

- Speed – source: Can Bus data or GPS data

- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- Message sent and received/Message content – Data logs
- Steering angle – source: Can Bus data
- System ODD – source: by design
- Fuel consumption – source: Can Bus data

Field Test Indicators – Modeling outputs

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

- Average Speed – source: Can Bus data or GPS data
 - Speed Standard Deviation – source: Can Bus data
 - Instantaneous accelerations and decelerations – source: Can Bus data
 - Reception point – source: GPS data and Can Bus data
 - Lane change point – source: Can Bus data or GPS data
 - Maximum steering angle – source: Can Bus data
 - Other lane average speed/average gap chosen by the HC system for the lane change – source: Can Bus data
 - Maximum jerk (rate of change in acceleration, longitudinal and lateral) – source: Can Bus data
 - Number of instances where the driver must take manual control – source: Can Bus data
 - Maximum braking value reached during a take-over request – source: Can Bus data
 - Fuel consumption – source: Can Bus data
 - Noise level – source: based on speed and on the aggressiveness of the driving regime
- [96]

Overview of the sub-research questions

Environment – Data requirements; Route parameters; Design choices	How does the lane change point vary (if the lane of the event is specified)? Are the accomplished lane changing maneuvers smoother?	Does the HC vehicle perform smoother braking thanks to the C-ITS message?
Message sent and received – Message content	X	X
Speed		X
Acceleration Deceleration		X
Position		X
Steering angle		X
System ODD		X
Fuel consumption	X	

Environment – Field test indicators and modeling outputs	How does the lane change point vary (if the lane of the event is specified)? Are the accomplished lane changing maneuvers smoother?	Does the HC vehicle perform smoother braking thanks to the C-ITS message?
Average speed		X
Speed Standard Deviation		X
Instantaneous acceleration and deceleration		X
Reception point		X
Lane change point		X
Maximum steering angle		X
Other lane average speed/average gap chosen by the HC system for the lane change		X

Environment – Field test indicators and modeling outputs	How does the lane change point vary (if the lane of the event is specified)? Are the accomplished lane changing maneuvers smoother?	Does the HC vehicle perform smoother braking thanks to the C-ITS message?
Maximum jerk	X	X
Number of instances where the driver must take manual control		X
Maximum braking value reached during a take-over request		X
Fuel consumption		X
Noise level		X

User Acceptance

Survey's Outputs

The following indicators should be collected after surveys:

- Situation awareness
- Knowledge about the Highway Chauffeur system and its capabilities
- Problem perception related to the approached hazardous location
- Perceived threats for the driver himself or for the workers on the road

- Perceived comfort during the maneuvers carried out by the HC vehicle, while passing the hazardous location

A.2.4. Hazardous Location Notification – Cluster 2: Traffic Jam Ahead

Traffic Efficiency

Data requirements – route parameters – design choices

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

- Message sent and received/Message content – Data logs
- Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- ACC pre - set parameters – source: Can Bus data
- Steering angle – source: Can Bus data
- Position – source: GPS data
- Traffic density – source: on road detectors or through modeling works
- Length of the queue – source: on-road detectors or modeling works
- Number of lanes hindered by the queue – Message data log

Field Test Indicators – Modeling Outputs

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

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation - source: Can Bus data or GPS data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Reception point – Can Bus data and GPS data
- ACC parameters chosen by the human driver – source: Can Bus data
- Time gap Accuracy/Stability – source: Can Bus data and/or equipped Sensors
- Maximum braking action – source: Can Bus data
- Maximum jerk (rate of change in acceleration, longitudinal and lateral) – source: Can Bus data
- Lane change point – source: Can Bus data or GPS data
- Maximum steering angle/action – source: Can Bus data

- Time needed for the queue to dissolve – source: On-road sensors, cameras or through modeling
- Travel time delay/ Time the HC vehicle gets stuck behind a queue – source: GPS data
- Dynamic capacity (i.e., the downstream outflow from traffic congestion) – source: on-road detectors or through modeling

Overview of the sub-research questions

Traffic Efficiency – Data requirements; Route parameters; Design choices	Is the HC vehicle's speed (more) compliant with the suggested speed limit?	How does the lane change point vary? Is the lane change maneuver carried out in a smoother way?	Does the Highway Chauffeur system follow the traffic control strategies suggested by the Traffic Control Centre or by the road operator? Does it adapt its time gaps and acceleration values to respond to the surrounding traffic conditions?	How do the instant speed fluctuations change?
Message sent and received – Message content	X	X	X	X
Speed	X		X	X
Acceleration Deceleration		X	X	X
Position	X	X	X	X
Steering angle		X		

Traffic Efficiency – Data requirements; Route parameters; Design choices	Is the HC vehicle's speed (more) compliant with the suggested speed limit?	How does the lane change point vary? Is the lane change maneuver carried out in a smoother way?	Does the Highway Chauffeur system follow the traffic control strategies suggested by the Traffic Control Centre or by the road operator? Does it adapt its time gaps and acceleration values to respond to the surrounding traffic conditions?	How do the instant speed fluctuations change?	
ACC pre-set parameters			X		
Number of lanes hindered by the queue					X
Length of the queue					X
Traffic Density					X

Traffic Efficiency – Field test indicators and modeling outputs	Is the HC vehicle's speed (more) compliant with the suggested speed limit?	How does the lane change point vary? Is the lane change maneuver carried out in a smoother way?	Does the Highway Chauffeur system follow the traffic control strategies suggested by the Traffic Control Centre or by the road operator? Does it adapt its time gaps and acceleration values to respond to the surrounding traffic conditions?	How do the instant speed fluctuations change?
Average speed	X			

Traffic Efficiency – Field test indicators and modeling outputs	Is the HC vehicle's speed (more) compliant with the suggested speed limit?	How does the lane change point vary? Is the lane change maneuver carried out in a smoother way?	Does the Highway Chauffeur system follow the traffic control strategies suggested by the Traffic Control Centre or by the road operator? Does it adapt its time gaps and acceleration values to respond to the surrounding traffic conditions?	How do the instant speed fluctuations change?
Speed Standard Deviation	X	X	X	X
Instantaneous acceleration and deceleration		X		X
Reception point		X		X
ACC parameters chosen by the human driver		X		X
Time Gap accuracy-stability		X		X
Maximum steering angle		X		
Maximum braking action				X

Traffic Efficiency – Field test indicators and modeling outputs	Is the HC vehicle's speed (more) compliant with the suggested speed limit?	How does the lane change point vary? Is the lane change maneuver carried out in a smoother way?	Does the Highway Chauffeur system follow the traffic control strategies suggested by the Traffic Control Centre or by the road operator? Does it adapt its time gaps and acceleration values to respond to the surrounding traffic conditions?	How do the instant speed fluctuations change?
Maximum jerk	X	X	X	X
Lane change point		X		
Other lane average speed/average gap chosen by the HC system to change lane		X		
Time needed for the queue to dissolve				
Travel time delay – time the HC vehicle gets stuck behind a queue				
Dynamic capacity				

Safety

Data requirements – route parameters – design choices

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

- Message sent and received/Message content – Data logs

- Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration or Brake pressure profile – source: Can Bus data or GPS data
- Position – source: GPS data
- Steering angle – source: Can Bus data
- Time To Collision (TTC) or similar metrics – source: Sensors data

Field Test Indicators – Modeling Outputs

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

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data or GPS data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Reception point – Can Bus data and GPS data
- Lane change point – source: Can Bus data or GPS data
- Maximum steering angle/action – source: Can Bus data
- Time gap Accuracy/Stability – source: Can Bus data and/or equipped Sensors
- Minimum TTC or similar metrics – source: Sensors data
- Number of events involving safety-critical values of TTC or similar metrics per km – source: Sensors data
- Number of emergency decelerations per km or miles – source: Can Bus data
- Time gaps chosen by the HC system for the lane changing maneuvers – source: Can Bus data

Overview of the sub-research questions

Safety – Data requirements; Route parameters; Design choices	Is the HC vehicle’s speed (more) compliant with the suggested value?	Does the HC vehicle perform a lane change maneuver to avoid the queue? Is this lane changing maneuver smoother?	How do the instant speed fluctuations change?
Message sent and received – Message content	X	X	X
Speed	X	X	
Acceleration Deceleration		X	X
Position	X	X	X
Steering angle		X	
TTC or equivalent metric		X	X
System ODD	X	X	X

Safety – Field test indicators and modeling outputs	Is the HC vehicle’s speed (more) compliant with the suggested value?	Does the HC vehicle perform a lane change maneuver to avoid the queue? Is this lane changing maneuver smoother?	How do the instant speed fluctuations change?
Average Speed	X		
Speed Standard Deviation	X	X	X
Instantaneous acceleration and deceleration		X	X
Reception point	X	X	X
Lane change point		X	
Maximum steering angle		X	
Time Gap accuracy – stability			X

Safety – Field test indicators and modeling outputs	Is the HC vehicle’s speed (more) compliant with the suggested value?	Does the HC vehicle perform a lane change maneuver to avoid the queue? Is this lane changing maneuver smoother?	How do the instant speed fluctuations change?	
Minimum TTC (or similar metrics) reached		X		
Number of events involving safety-critical values of TTC or similar metrics/ km driven		X		X
Number of emergency decelerations per km				X
Other lane average speed/gap chosen by the HC system for the lane change		X		X

Environment

Data requirements – route parameters – design choices

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

- Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- Message sent and received/Message content – Data logs
- ACC pre-set parameters – source: ACC system and Can Bus data
- Steering angle – source: Can Bus data
- Market penetration of ACC-equipped vehicles among the traffic flow
- Fuel consumption – source: Can Bus data

Field Test Indicators – Modeling outputs

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

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Reception point – source: GPS data and Can Bus data
- Lane change point – source: Can Bus data or GPS data
- Maximum steering angle/action – source: Can Bus data
- Other lane average speed/gap chosen by the HC system to perform the lane change– source: Can Bus data
- Maximum jerk (rate of change in acceleration, longitudinal and lateral) – source: Can Bus
- Maximum braking value reached – source: Can Bus data
- Fuel consumption – source: Can Bus data
- Noise level – source: based on speed and on the aggressiveness of the driving regime

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Overview of the sub-research questions

Environment – Data requirements; Route parameters; Design choices	Is the HC vehicle’s speed (more) compliant with the suggested value?	Does the HC vehicle perform a lane change maneuver to avoid the queue? Is this lane changing maneuver smoother?	How do the instant speed fluctuations change thanks to the messages received?	Does the Highway Chauffeur system adapt its longitudinal control law once the C-ITS message is received and the queue is signaled?
Message sent and received – Message content	X	X	X	X
Speed	X			X

Environment – Data requirements; Route parameters; Design choices	Is the HC vehicle’s speed (more) compliant with the suggested value?	Does the HC vehicle perform a lane change maneuver to avoid the queue? Is this lane changing maneuver smoother?	How do the instant speed fluctuations change thanks to the messages received?	Does the Highway Chauffeur system adapt its longitudinal control law once the C-ITS message is received and the queue is signaled?
Acceleration Deceleration	X	X	X	X
Position		X		X
Steering angle		X		
ACC pre-set parameters				X
Market penetration of ACC-equipped vehicles among the traffic flow				X
System ODD				X
Fuel consumption				X

Environment – Field test indicators and modeling outputs	Is the HC vehicle's speed (more) compliant with the suggested value?	Does the HC vehicle perform a lane change maneuver to avoid the queue? Is this lane changing maneuver smoother?	How do the instant speed fluctuations change thanks to the messages received?	Does the Highway Chauffeur system adapt its longitudinal control law once the C-ITS message is received and the queue is signaled?
Average speed	X			X
Speed Standard Deviation	X	X	X	X
Instantaneous acceleration and deceleration		X	X	X
Reception point	X	X	X	X
Lane change point		X		
Maximum steering angle		X		
Other lane average speed/gap chosen by the HC system to perform the lane change		X		

Environment – Field test indicators and modeling outputs	Is the HC vehicle’s speed (more) compliant with the suggested value?	Does the HC vehicle perform a lane change maneuver to avoid the queue? Is this lane changing maneuver smoother?	How do the instant speed fluctuations change thanks to the messages received?	Does the Highway Chauffeur system adapt its longitudinal control law once the C-ITS message is received and the queue is signaled?
Maximum jerk		X	X	X
Maximum braking value reached			X	
Fuel consumption	X	X	X	X
Noise level	X	X	X	X

User Acceptance

Survey’s Outputs

The following indicators should be collected after surveys:

- Situation awareness
- Knowledge about the Highway Chauffeur system and its capabilities
- Perceived comfort during the maneuvers carried out by the HC vehicle, while passing the hazardous location
- Propensity to let the Highway Chauffeur system adapt the values of speed and time gap, according to the situation of the surrounding traffic

A.2.5. Hazardous Location Notification – Cluster 3: Weather Condition Warning – Temporary Slippery Road

Traffic Efficiency

Data requirements – route parameters – design choices

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

- Message sent and received/Message content – Data logs
- Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- System ODD – source: by design
- Steering angle – source: Can Bus data
- Road grade
- Light conditions – source: Sensors data
- Characteristics of the weather condition – source: Weather records

Field Test Indicators – Modeling outputs

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

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Reception point – Can Bus data and GPS data
- Maximum jerk (rate of change in acceleration, longitudinal and lateral) – source: Can Bus data
- Maximum steering angle – source: Can Bus data
- Time Gap Accuracy/Stability or Error in Spacing – source: Radar and GPS
- Number of emergency decelerations per km or miles – source: Can Bus data
- Take-over triggers – source: Can Bus data
- Take-over mean time – source: Can Bus data
- Take-over maximum time – source: Can Bus data
- Maximum braking action reached during a take-over maneuver – source: Can Bus data
- Minimum distance from lateral boundaries – source: Cameras

Overview of the sub-research questions

Traffic Efficiency – Data requirements; Route parameters; Design choices	Does the HC vehicle surpass the spillage without re-engaging the driver?	How does the lane change point vary? (if the lane of the event is specified)	Is the take-over transition smoother?	Does the driver re-engage the driving task without braking or swerving, in time to reach the signaled section with a fully regained situational awareness?	Does a vehicle suddenly made “blind” by an adverse weather condition take itself to the nearest safe state? Does the message forwarded by the Adverse Weather Condition Use Case prevent this kind of scenario?	Does the HC vehicle surpass the hazardous section without re-engaging the driver?
Message sent and received – Message content	X	X	X	X	X	X
Speed	X		X		X	X
Acceleration Deceleration			X	X	X	X
Position	X	X	X	X	X	X
Steering angle	X	X	X	X		
Road grade						X

Traffic Efficiency – Data requirements; Route parameters; Design choices	Does the HC vehicle surpass the spillage without re-engaging the driver?	How does the lane change point vary? (if the lane of the event is specified)	Is the take-over transition smoother?	Does the driver re-engage the driving task without braking or swerving, in time to reach the signaled section with a fully regained situational awareness?	Does a vehicle suddenly made “blind” by an adverse weather condition take itself to the nearest safe state? Does the message forwarded by the Adverse Weather Condition Use Case prevent this kind of scenario?	Does the HC vehicle surpass the hazardous section without re-engaging the driver?		
Light conditions	X		X		X	X		
Characteristics of the weather condition							X	X
System ODD							X	X

Traffic Efficiency – Field test indicators and modeling outputs	Does the HC vehicle surpass the spillage without re-engaging the driver?	How does the lane change point vary? (if the lane of the event is specified)	Is the take-over transition smoother?	Does the driver re-engage the driving task without braking or swerving, in time to reach the signaled section with a fully regained situational awareness?	Does a vehicle suddenly made “blind” by an adverse weather condition take itself to the nearest safe state? Does the message forwarded by the Adverse Weather Condition Use Case prevent this kind of scenario?	Does the HC vehicle surpass the hazardous section without re-engaging the driver?
Average speed		X	X		X	X

Traffic Efficiency – Field test indicators and modeling outputs	Does the HC vehicle surpass the spillage without re-engaging the driver?	How does the lane change point vary? (if the lane of the event is specified)	Is the take-over transition smoother?	Does the driver re-engage the driving task without braking or swerving, in time to reach the signaled section with a fully regained situational awareness?	Does a vehicle suddenly made “blind” by an adverse weather condition take itself to the nearest safe state? Does the message forwarded by the Adverse Weather Condition Use Case prevent this kind of scenario?	Does the HC vehicle surpass the hazardous section without re-engaging the driver?
Speed Standard Deviation		X	X			
Instantaneous accelerations and decelerations		X	X	X	X	X
Reception Point	X	X	X	X	X	X
Maximum jerk		X	X	X	X	X
Maximum steering angle	X	X				
Time Gap accuracy – stability				X	X	X
Number of emergency braking per km driven	X		X		X	X

Traffic Efficiency – Field test indicators and modeling outputs	Does the HC vehicle surpass the spillage without re-engaging the driver?	How does the lane change point vary? (if the lane of the event is specified)	Is the take-over transition smoother?	Does the driver re-engage the driving task without braking or swerving, in time to reach the signaled section with a fully regained situational awareness?	Does a vehicle suddenly made “blind” by an adverse weather condition take itself to the nearest safe state? Does the message forwarded by the Adverse Weather Condition Use Case prevent this kind of scenario?	Does the HC vehicle surpass the hazardous section without re-engaging the driver?
Take-over triggers	X				X	X
Take-over mean time				X	X	
Take-over maximum time				X	X	
Maximum braking action during a take-over maneuver			X	X		
Minimum distance from lateral boundaries	X	X		X	X	

Safety

Data requirements – route parameters – design choices

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

- Message sent and received/Message content – Data logs
- Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data

- ACC parameters – source: ACC system and Can Bus data
- Steering angle – source: Can Bus data
- Warning delivery strategy: Visual, auditory, haptic or a combination of the above
- Time to Collision or similar metrics – source: Sensors data
- System ODD – source: by design
- Road grade
- Number of lanes hindered by the event – source: Message data log

Field Test Indicators – Modeling outputs

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

- Average Speed – source: Can Bus data or GPS data
- Speed Standard Deviation – source: Can Bus data
- Instantaneous accelerations and decelerations – source: Can Bus data
- Reception point – Can Bus data and GPS data
- Maximum jerk (rate of change in acceleration, longitudinal and lateral) – source: Can Bus data
- Lane change point – source: Can Bus data or GPS data
- Maximum steering angle – source: Can Bus data
- Other lane average speed/gap chosen by the HC system for the lane change – source: Can Bus data
- Traffic densities beyond which the lane changing maneuver is hindered – source: on-road detectors and Can Bus data or through modeling works
- Minimum TTC or similar metrics – source: Sensors data
- Number of events involving safety-critical values of TTC or similar metrics – source: Sensors data
- Lateral Position Standard Deviation – source: Can Bus data
- Time gap Accuracy/Stability – source: Can Bus data and/or equipped Sensors
- Number of emergency braking per km or miles – source: Can Bus data
- Number of instances where the driver must take manual control, triggered by the hazardous event – source: Can Bus data

Overview of the sub-research questions

Safety – Data requirements; Route parameters; Design choices	Does the lane change point vary? Is the lane changing maneuver smoother? (if the lane of the event is signalled)	If the HC vehicle can't avoid the spillage, is the take-over maneuver accomplished in advance, in a smoother and safer way?	Does the HC vehicle's speed decreases before reaching the slippery section? Does the information prevent the HC vehicle from passing through the spillage at high velocity?	Does the received information give details about road adhesion that the perceiving system isn't able to detect?	Does the take-over maneuver happen in a smoother and safer way?	Does the average speed decrease?	Does a vehicle suddenly made "blind" by an adverse weather condition take itself to the nearest safe state?
Message sent and received – Message content	X	X	X	X	X		X
Speed		X	X	X	X	X	X
Acceleration Deceleration	X	X		X	X		X
Steering angle	X	X		X	X		X
ACC pre-set parameters			X	X			
TTC or equivalent metrics	X	X	X	X	X	X	X
Warning delivery strategy		X			X		X

Safety – Data requirements; Route parameters; Design choices	Does the lane change point vary? Is the lane changing maneuver smoother? (if the lane of the event is signalled)	If the HC vehicle can't avoid the spillage, is the take-over maneuver accomplished in advance, in a smoother and safer way?	Does the HC vehicle's speed decrease before reaching the slippery section? Does the information prevent the HC vehicle from passing through the spillage at high velocity?	Does the received information give details about road adhesion that the perceiving system isn't able to detect?	Does the take-over maneuver happen in a smoother and safer way?	Does the average speed decrease?	Does a vehicle suddenly made "blind" by an adverse weather condition take itself to the nearest safe state?
Number of lanes hindered by the event	X						
Road grade			X	X			X
System ODD	X		X	X			X

Safety – Field test indicators and modeling output	Does the lane change point vary? Is the lane changing maneuver smoother? (if the lane of the event is signalled)	If the HC vehicle can't avoid the spillage, is the take-over maneuver accomplished in advance, in a smoother and safer way?	Does the HC vehicle's speed decrease before reaching the slippery section? Does the information prevent the HC vehicle from passing through the spillage at high velocity?	Does the received information give details about road adhesion that the perceiving system isn't able to detect?	Does the take-over maneuver happen in a smoother and safer way?	Does the average speed decrease?	Does a vehicle suddenly made "blind" by an adverse weather condition take itself to the nearest safe state?
Average speed		X	X	X	X	X	X
Speed Standard Deviation	X	X	X	X	X	X	X

Safety – Field test indicators and modeling output	Does the lane change point vary? Is the lane changing maneuver smoother? (if the lane of the event is signalled)	If the HC vehicle can't avoid the spillage, is the take-over maneuver accomplished in advance, in a smoother and safer way?	Does the HC vehicle's speed decreases before reaching the slippery section? Does the information prevent the HC vehicle from passing through the spillage at high velocity?	Does the received information give details about road adhesion that the perceiving system isn't able to detect?	Does the take-over maneuver happen in a smoother and safer way?	Does the average speed decrease?	Does a vehicle suddenly made "blind" by an adverse weather condition take itself to the nearest safe state?
Instantaneous accelerations and decelerations	X	X		X	X		X
Reception point	X	X	X	X	X	X	X
Maximum jerk	X	X	X	X	X		X
Maximum steering angle	X	X		X	X		X
Lane change point	X						
Other lane average speed/gap chosen by the HC system for the lane change	X						
Lateral position standard deviation	X	X			X		X

Safety – Field test indicators and modeling output	Does the lane change point vary? Is the lane changing maneuver smoother? (if the lane of the event is signalled)	If the HC vehicle can't avoid the spillage, is the take-over maneuver accomplished in advance, in a smoother and safer way?	Does the HC vehicle's speed decrease before reaching the slippery section? Does the information prevent the HC vehicle from passing through the spillage at high velocity?	Does the received information give details about road adhesion that the perceiving system isn't able to detect?	Does the take-over maneuver happen in a smoother and safer way?	Does the average speed decrease?	Does a vehicle suddenly made "blind" by an adverse weather condition take itself to the nearest safe state?
Traffic densities beyond which the lane changing maneuver is hindered	X						
Minimum TTC or similar metrics	X	X	X	X	X		X
Number of events involving safety critical values of TTC (or similar metrics)	X	X	X	X	X		X
Time Gap accuracy - stability				X			X
Number of emergency braking per km driven		X	X	X	X		X
Number of instances where the driver must take manual control, triggered by the hazardous event		X	X	X	X		X

Environment

Data requirements – route parameters – design choices

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

- Speed – source: Can Bus data or GPS data
- Acceleration/Deceleration – source: Can Bus data or GPS data
- Position – source: GPS data
- Message sent and received/Message content – Data logs
- Steering angle – source: Can Bus data
- System ODD – source: by design
- Road grade
- Fuel consumption – source: Can Bus data

Field Test Indicators – Modeling outputs

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

- Average Speed – source: Can Bus data or GPS data
 - Speed Standard Deviation – source: Can Bus data
 - Instantaneous accelerations and decelerations – source: Can Bus data
 - Reception point – source: GPS data and Can Bus data
 - Lane change point – source: Can Bus data or GPS data
 - Maximum steering angle – source: Can Bus data
 - Other lane average speed/gap chosen by the HC vehicle for the lane change – source: Can Bus data
 - Maximum jerk (rate of change in acceleration, longitudinal and lateral) – source: Can Bus data
 - Number of instances where the driver must take manual control – source: Can Bus data
 - Maximum braking value reached during a take-over request – source: Can Bus data
 - Fuel consumption – source: Can Bus data
 - Noise level – source: based on speed and on the aggressiveness of the driving regime
- [96]

Overview of the sub-research questions

Environment – Data requirements; Route parameters; Design choices	Does the HC vehicle perform the lane changing maneuver in a smoother way to avoid the spillage?	Does the information forwarded by the service foster smoother decelerations while the HC vehicle approaches an unavoidable spillage?	Does the information forwarded in advance make the take-over maneuvers smoother, avoiding harsh braking performed by the human driver?
Message sent and received – Message content	X	X	X
Speed		X	
Acceleration Deceleration		X	
Position		X	
Steering angle		X	
Road grade		X	
System ODD		X	

Environment – Data requirements; Route parameters; Design choices	Does the HC vehicle perform the lane changing maneuver in a smoother way to avoid the spillage?	Does the information forwarded by the service foster smoother decelerations while the HC vehicle approaches an unavoidable spillage?	Does the information forwarded in advance make the take-over maneuvers smoother, avoiding harsh braking performed by the human driver?
Fuel consumption	X	X	X

Environment – Field test indicators and modeling outputs	Does the HC vehicle perform the lane changing maneuver in a smoother way to avoid the spillage?	Does the information forwarded by the service foster smoother decelerations while the HC vehicle approaches an unavoidable spillage?	Does the information forwarded in advance make the take-over maneuvers smoother, avoiding harsh braking performed by the human driver?
Average speed	X	X	X
Speed Standard Deviation		X	
Instantaneous accelerations and decelerations		X	
Reception point		X	

Environment – Field test indicators and modeling outputs	Does the HC vehicle perform the lane changing maneuver in a smoother way to avoid the spillage?	Does the information forwarded by the service foster smoother decelerations while the HC vehicle approaches an unavoidable spillage?	Does the information forwarded in advance make the take-over maneuvers smoother, avoiding harsh braking performed by the human driver?
Maximum jerk	X	X	X
Maximum steering angle	X		X
Lane change point	X		
Other lane average speed/gap chosen by the HC system for the lane change	X		
Number of instances where the driver must take manual control	X	X	X
Maximum braking value reached during a take-over request	X	X	X
Fuel consumption	X	X	X

Environment – Field test indicators and modeling outputs	Does the HC vehicle perform the lane changing maneuver in a smoother way to avoid the spillage?	Does the information forwarded by the service foster smoother decelerations while the HC vehicle approaches an unavoidable spillage?	Does the information forwarded in advance make the take-over maneuvers smoother, avoiding harsh braking performed by the human driver?
Noise level	X	X	X

User Acceptance

Survey's Outputs

The following indicators should be collected after surveys:

- Situation awareness
- Knowledge about the Highway Chauffeur system and its capabilities
- Perceived comfort during the maneuvers carried out by the HC vehicle, while passing the hazardous location
- Perceived usefulness of the information broadcasted by the service, related to the utility for the Highway Chauffeur system
- Propensity to let the Highway Chauffeur system keep driving in automated mode through an adverse weather condition
- Number of false positives and false negatives related to the take-over maneuver before an adverse weather condition

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