Highway Chauffeur: state of the art and future evaluations

Implementation scenarios and impact assessment

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***Abstract*—A transition phase is currently featuring the automotive world, with the car being everyday less a simple tool and more an active assistant for the driver. Many automated functions are already implemented in cars (e.g. Adaptive Cruise Control, Lane Keeping Assistant, etc.); the very next step towards a fully automated vehicle is represented by the deployment of a car able to handle both longitudinal and lateral control for a limited amount of time, keeping the driver out of the driving loop and effectively accomplishing the driving task in a well-defined domain. The Highway Chauffeur system falls in this category and is, therefore, a perfect candidate to move another step towards full automation. Scope of this paper is to define some of the most well-established implementation scenarios on the basis of a bibliographical review. This activity is aimed at identifying the operational schemes most likely to happen in the near future which are, then, employed to derive some of the most relevant research questions to assess the future impact of the system on Traffic Efficiency and Environment.**

Keywords: Automated driving; L3 system; Highway Chauffeur; Traffic Jam Chauffeur; C-ITS; C-Roads; Impact assessment; Cooperative services.

I. INTRODUCTION

Considering the current SAE classification [2], it can be stated that many L2 system are already able to drive on public roads in many countries. Therefore, one of the next steps towards complete automation is represented by the deployment of an L3 vehicle able to keep the human driver completely out of the driving loop, even if for a limited amount of time. To achieve this task, a well-defined design domain must be defined, in which the automated system is guaranteed to operate until the destination is reached or some external event occurs (e.g. system failure, sudden change in weather condition, etc.); in these circumstances the vehicle should issue a take-over request and the human driver should re-engage the driving task. The necessity to precisely define an Operational Design Domain (ODD) makes an environment such as the highway one much more suited for an L3 system, rather than, for example, one as heterogeneous as the urban one.

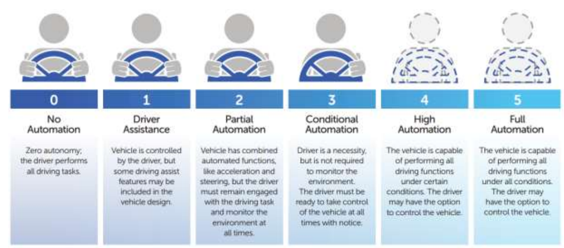

Figure I-1: SAE levels of automation [4]

Therefore, the scope of this article is to characterize the most likely implementation scenarios of the Highway Chauffeur system to define the possible impacts on Traffic Efficiency and Environment, highlighting both barriers and solutions to accomplish this assessment and design appropriate field tests or modeling works. The paper is structured as it follows: in section II an overview of the Highway Chauffeur system is presented, in section III the most promising longitudinal control laws and strategies are analyzed from literature while in section IV the motion planning process and the lateral control laws are reported. Then, in section V, the most likely implementation scenarios are described, highlighting what is still uncertain and what depends on the OEM choice. Moreover, other subjects worth studying are presented. Lastly, in section VI, the impacts of the described system on the impact areas Traffic Efficiency and Environment are identified qualitatively (reporting the most common values in literature, if existing) and in section VII conclusions and future research directions are presented.

II. HIGHWAY CHAUFFEUR SYSTEM

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 [3]. While the Highway Chauffeur system is engaged, both longitudinal and lateral control are entrusted to the vehicle, while the human driver can exit the driving loop and engage secondary tasks. To achieve this task, the vehicle (referred as HC vehicle from now on) must scan continuously the environment to understand if it can guarantee acceptable levels of safety to both the human driver and the surrounding road users. If the ODD is left because of changes in the surrounding environment or of system failures, a take-over request is issued to the driver that must abandon his secondary task, re-assess an acceptable level of situational awareness and re-engage the driving task. If the driver doesn't answer or he is unable to, the system must be able to take the vehicle to a minimum risk condition which may include slowing it down and/or reach a safe stop. In this paper an HC vehicle is considered able to exploit both the Highway Chauffeur function and the Traffic Jam Chauffeur function, covering the speed range of 0-130 km/h. In [5] it is stated that the former function can accomplish also lane changing maneuvers while the latter function both overtaking and lane changing maneuvers. The technological equipment needed for the vehicle to accomplish the driving task is composed at least by Adaptive Cruise Control, Lane Keeping and Lane Changing Assist, Automated Braking System and Front Collision Warning. In [6] an overview of the most common components and their market maturity is reported in relationship with the various state of automation. In [7] an inclusive review of the available sensor technologies has been carried out: an HC vehicle should at least be equipped with radars, LIDARs (that are also analyzed in [8]), cameras and ultrasonic sensors. In [9], instead, the sensor suite used to test the BMW automated driving prototype vehicle on highways is described. In addition to the equipment mentioned above, important sources of information can be Dedicated Short Range Communications that allow the HC vehicle to communicate both with the surrounding road users and with the infrastructure. The opportunities of these V2X communications are explicitly mentioned, for example, in ([8], [10], [11], [12]) to enhance both the perception of the automated system and its operational efficiency. For the system to work as intended, the huge amount of information received must be combined through sensor data fusion and processed through the software and the hardware components to define a feasible trajectory and activate the lower controls. The HC vehicle defined in the present article is considered able to exploit the possibilities of V2X communications and it is considered, therefore, automated but not autonomous (as explained in [10]) as long as the system is engaged.

III. Longitudinal Control

The longitudinal control of a vehicle is accomplished by setting both the speed value and the acceleration/deceleration regime. In the HC vehicle this task is carried out thanks to the Adaptive Cruise Control that uses only on-board sensors to determine the distance between the HC vehicle and the preceding one as well as the speed difference between them. The driver can set any desired speed value between 60 – 130 km/h as a cruise value that can be kept in free flow conditions or until a slower vehicle appears in front of the HC vehicle. When a slower vehicle is approached, instead, the ACC allows the HC vehicle to maintain a desired time gap between itself and the slower vehicle (the time gap value can be set by the human driver and can range between 0.8 s to 2.5 s). Leaving the choice of the functional parameters to the human driver causes in literature, a relevant uncertainty about the potential impacts on the traffic flow. It should also be highlighted that an ACC system can decrease substantially both perception and reaction times when compared to the human ones, as showed in [14].

In [11] a traffic-adaptive control strategy for ACC-equipped vehicles is presented. An important assumption is that the ACC parameters can be dynamically updated to achieve improved traffic flow conditions, overriding the preferences set by the human driver in some traffic scenarios. This hypothesis is not so limiting when considering an engaged Highway Chauffeur system in which the driver is probably both distracted and entertained by the secondary task. The control strategy presented in [11] is implemented through a strategic level that changes the ACC parameters on the basis of the surrounding flow conditions, these changes can be triggered by V2X communications or by what is perceived by the sensor suite. An overview of the different situations that can trigger a change is reported in fig.1 [11].

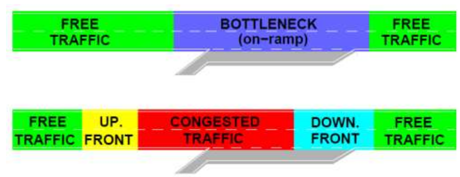

Fig. III-1: Functioning logic of the strategic layer

Positive impacts on Traffic Efficiency are not reachable by means of ACC-equipped vehicles alone, but the potentialities of an increasing percentage of HC vehicles among the traffic flow shouldn't be overlooked.

In [15], the authors assessed the effects induced on traffic flow by an ACC-equipped vehicle responding to a change of speed in the preceding vehicle through a macroscopic gas-kinetic traffic flow model. From the simulations carried out by the authors a more stable traffic flow regime is obtained when the ACC system is implemented, even considering a time gap of 1.2 s. Moreover, simulations to evaluate also the Stop&Go regime have been carried out and showed that the presence of ACC vehicles among the traffic flow dampened perturbations and delayed or avoided the congestion. Another study that analyzes the impact on the traffic flow of a longitudinally automated vehicle controlled by a well-tuned algorithm is [16]. This work 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. Two control strategies are evaluated through a closed ring test: FollowerStopper controller (that relies also on external sources of information) and proportional-integral controller with saturation (that relies only on on-board sensors). Both resulted able to dampen the effect of shockwaves, lowered fuel consumption and increased the traffic throughput (the latter resulted in a reduction of the average speed, though). Relevant benefits for Traffic Efficiency and Environment were obtained. What the ACC system can achieve alone is analyzed in [13], in a more conservative way, without considering dedicated algorithms and control strategies or external inputs. Therefore, the ACC system alone, simply managed by the human driver, is studied. Different time gaps are evaluated: 2.2 s, 1.6 s and 1.1 s. The simulations showed that the percentage of vehicles with automated longitudinal control among the traffic flows doesn't seem to affect capacity. Based on what is reported in this section it can be concluded that it is difficult to assess the impact that a fair share of autonomously longitudinally controlled vehicles can determine because both the parameters and the implementable control rules aren't univocal and depend strongly by the single OEM choices. It can be stated, though, that enough ACC-equipped vehicles travelling on a highway represent a huge potentiality for both Traffic Efficiency and Environment, if coordinated or designed in a suited way and that the possibilities granted by an automated system already available on the market (such as the ACC) shouldn't be overlooked.

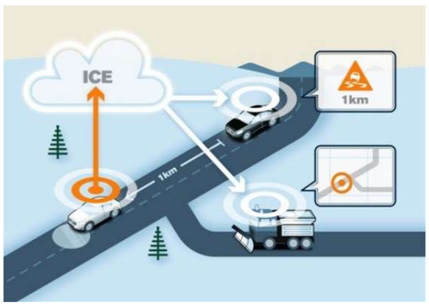

Figure III-2:Example of V2X communications benefits of the Volvo DriveMe program [14]

IV. LATERAL CONTROL AND MOTION PLANNING

As discussed in the previous section, to retain longitudinal control, a rather small set of parameters and environmental inputs must be considered and the main decisions concern the acceleration/deceleration regime. For lateral control, instead, 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 the maneuver itself. Besides, the HC vehicle must be conscious and evaluate the most likely behavior of the other road users, their future acceleration values and driving direction. The lateral control of the HC vehicle has different impacts compared to the ones achievable by the longitudinal control law: the HC vehicle can perform both more or less efficient maneuvers (overtaking, lane changing, ramp interactions) on the basis of the aggressiveness of the driving style implemented in the control algorithm. Again, this depends on the choices of the single OEMs and can't be evaluated a priori. On the basis of the literature review the most likely scenarios have been assessed, though, and used to derive the possible impacts of the Highway Chauffeur system.

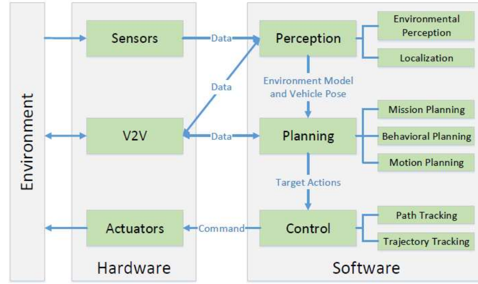

Fig. IV-1:Software and Hardware for autonomous driving [8]

In [8] an overview of the functioning logic of software systems is provided, highlighting the core competencies such as perception, planning and control. Also in this work, the possibilities offered by V2V communications are mentioned. In fig.2 "Perception" allows 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 [8]. Motion planning is the phase during which the action needed to reach the planned goal are determined scanning all the possible spaces occupied by obstacles and acting accordingly.

In [17] an algorithm called the AutonoVi is presented. The control laws allowed lane changing, swerving and braking while considering the vehicle dynamics, the surrounding traffic and the environmental perception accomplished by the sensor suite. It is important to note that the algorithm developed by the authors is able to determine when a lane changing maneuver is appropriate and encourages it as long as safety is guaranteed. Thus, a less conservative approach is assumed which is relevant to the impact assessment of the Highway Chauffeur system because highlights how the HC vehicle can both adapt its driving behavior to be more passive (keeping the lane despite an increased travel time) or favor lane changing and overtaking maneuver to minimize travel time. In [17] an optimization process is carried out to evaluate the upcoming maneuvers on the basis of a cost function.

Another work focused on the lane changing maneuver of an automated vehicle driving on a highway is [18], in which the lane change is started if deemed appropriate on the basis of a cost function and the control laws are computed through a Model Predictive Control. A relevant characteristic is that the changing behavior of the surrounding road users during the time interval considered for the estimations is predicted probabilistically. Therefore, safety is guaranteed by the system that computes the future state of the surrounding vehicles and defines an environmental envelope that guarantees sufficient values of the Time to Collision metric.

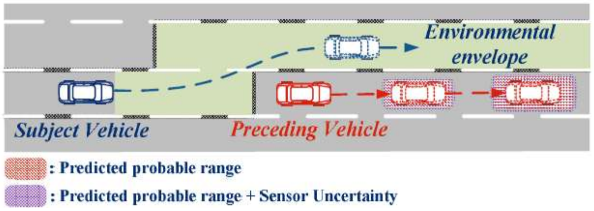

Fig. IV-2: Lane changing maneuver and Safety [18]

Uncertainties bound to the dynamic driving environment are surely a problematic issue for a system that aims to drive without involving the human driver. In [19] these uncertainties are considered while defining a trajectory planning for autonomous vehicles that still retains safety. It should be highlighted that an HC vehicle can be considered automated as long as it operates in its ODD. The algorithm defines a maximum acceptable collision probability, 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.

In [12] a review of motion planning methods for automated vehicles is carried out, with a focus on the most acknowledged methods and techniques used to decompose the space, on the risk estimation that must be carried out while evaluating future maneuvers and on the limitations that an automated system must be able to face. Besides, the authors explicitly mention the need for data collection during field tests, so to effectively calibrate the control algorithms. One step in this direction is going to be performed with the activities planned within C-Roads Italy[1] in the next years. Field tests meant to assess the impact of a jointed implementation of a Highway Chauffeur system and of the C-ITS Day 1services will be carried out, indeed.

V. Scenarios of implementation and follow-up subjects

On the basis of what has been reported on the paragraphs above, should emerge a picture of what an HC vehicle can accomplish while interacting with the surrounding road users, which maneuvers can be carried out and what effects these can impose on the surrounding traffic flow should emerge. Moreover, the elements that still have to be defined and can strongly change the results are highlighted (i.e. time gaps, aggressiveness of the control algorithms, frequency of the lane changing maneuvers and maximum accelerations and decelerations). An HC vehicle will most likely be able to handle light adverse weather conditions while the perception of lane markings during snowfalls is still challenging. It should be highlighted how, by exploiting V2X communications and C-ITS services, the vehicle can perform better during these events or, at least, issue in advance the take-over request to the human driver. An HC vehicle will be able to perform both car following and lane changing or overtaking maneuvers; though, it is still to be defined what aggressiveness level will be assumed. There is also the possibility that the Highway Chauffeur systems on the market will grant the driver with the possibility to choose between different levels of aggressiveness, thus making the evaluation task even more complex. Evaluations should be developed with different ACC time gaps values, ranging between 0.8 and 2 s, and different levels of market penetration. Different traffic control strategies should be analyzed, considering algorithms not only oriented to driver's comfort, but also to the overall efficiency of the traffic flow.

Before presenting the assessed impacts both on Traffic Efficiency and Environment, preliminary considerations should be presented. First, an important subject is not deeply analyzed in this paper (it will be done in dedicated and specific publications within C-Roads Italy activities) but can't be ignored: the take-over maneuver. The transition in control between the Highway Chauffeur system and the human driver (and vice versa) clearly affects safety but impacts also on Traffic Efficiency and Environment, possibly involving abrupt maneuvers such as harsh braking in response. A driver which is not alerted in advance or in a functional way can perform braking actions more abrupt than necessary or swerving behaviors. Both these sub-optimal behaviors can impact on the surrounding traffic causing perturbations upstream the traffic flow. The efficiency of the take-over maneuver can be guaranteed through a well-designed HMI, warning strategies tuned on the urgency of the take-over and clear information provided to the system also through V2X communications. All these factors strongly depend by OEMs choices and are difficult to assess in general without referring to a specific product. A more complete dissertation is going to be provided by C-Roads Italy, though, considering also the possibilities exploitable by the additional information provided by the C-ITS Day 1 Services. In fact, the information granted through V2X communication can inform the system about events ahead that fall out of its ODD, therefore fostering an earlier and smoother take-over transition and lesser perturbations upstream the traffic flow.

VI. Impact Assessment

About impacts, this paper is not intended to derive numerical results referred to a specific operational framework but to qualitatively identify the impacts of an L3 system on two impact areas [1]: Traffic Efficiency and Environment. Where possible, it is defined if the impacts are expected to be positive or negative while, where this evaluation depends on the control parameters cited in the previous paragraphs, it is highlighted how these relationships affect Traffic Efficiency and Environment.

For Traffic Efficiency the formulated research questions are:

- How conservative is the behavior of the automated system?
- Does the HC system avoid lane changing and overtaking, when unnecessary?
- Are the lane changing maneuvers carried out in a more efficient way?
- Is the ACC time gap set up by the drivers during automated driving higher, lower or the same as the one characterizing human driving?
- Is the HC vehicle's longitudinal control overall more efficient than the human one?
- Does the HC vehicle adapt its time gap value while approaching highway entrance ramps?

[1] The main goal of the C-Roads ITALY project is to implement and test, in real traffic conditions, both cooperative systems and passenger cars equipped with the Highway Chauffeur system

- Does the system exploits information from traffic control centers or other external service provider to adapt its driving regime and ease the traffic flow conditions?
- Does the Traffic Jam Chauffeur ease the traffic congestion, promoting an earlier return to the decongested state?

These questions are useful to define what must be assessed by future evaluators while designing field tests or modeling works. For example, it can be stated that having a fair share of vehicles driving with the Traffic Jam Chauffeur engaged among a queue can ease the congestion, at least assuring an optimal Stop&Go regime even for a long time. Depending on the ACC parameters set, road capacity can both increase or decrease, though, and through modeling works it should be assessed how these parameters influence the traffic flow. A negative effect that can arise is bound to the frequency of the lane changing maneuver performed by the HC vehicles, when the driver is out of the driving loop, the time is no longer perceived as lost and a more conservative driving style can be accepted. On the other hand, if the system avoids sudden lane changing maneuvers, it doesn't produce perturbations and shockwaves upstream, nullifying the flaws of the human driving bound to lane changing and overtaking. It should be noted that the distinction is not, 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 fewer but smoother lane changes. As long as the longitudinal control is concerned, instead, it should be evaluated how the impact of the Highway Chauffeur system varies depending on the feasible time gaps and what are the potentialities exploitable by issuing an adaptation of the time gap among HC vehicles approaching or facing a congested section. The effect can be both negative, if the held time gap is equal or wider than the human one, or positive because an automated system constantly scans 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 interactions with other vehicles. This, in turn, should foster an increased traffic efficiency.

To assess the impacts of the Highway Chauffeur system, both field tests and modeling activities can be employed. A field test can be used to validate the ODD of the system implemented and to obtain some "behavioral" 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 use these outputs to evaluate the impacts on the overall traffic flow, in different scenarios and with different levels of market penetration.

For Environment the formulated research questions are:

- Does a more efficient longitudinal control foster a decrease in fuel consumption?
- Does the HC driving synergize with the electric vehicle's technology assuring a more energy efficient driving behavior?
- 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?
- Do traffic management strategies that exploit the presence of automated vehicles on the road prevent or reduce congestion?
- 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?
- Does the Traffic Jam Chauffeur foster a more energy efficient Stop&Go driving and smoother braking actions?

The main effect on the environment and emissions is surely related to the efficiency of the overall traffic flow, thus depends on the same operational parameters and hypothesis commented in the Traffic Efficiency impact area. There are other mechanisms concerning environmental issues, that could arise from the deployment of the Highway Chauffeur system. As stated for example in [21], 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. Moreover, the aggressiveness of the algorithm can vary the number of overtaking maneuvers performed, resulting in a lower or higher number of accelerations and decelerations and changing, therefore, fuel consumption. Another subject worth studying and mentioned in ([6], [21], [22]) concerns both electric vehicles and the possibilities offered by the automation. In fact, plug-in electric vehicles are considered perfect candidates for automated driving thanks, for example, to their drive-by-wire controls and electric actuation systems [21]. Besides a better management of acceleration, cruising, slowing and stopping should synergize well with electric propulsion. As long as the smoothness of the accomplished maneuvers is concerned, it should be highlighted how lane changing maneuvers will be most likely started by an HC vehicle only if the perception system judges the gaps on the other lane to be wide enough, thus limiting the number of harsh and sudden braking imposed to the following vehicles. This, in turn, should decrease their emission levels. Another effect that could arise concerns the involvement of the human driver in a secondary task: as stated in [22], an automated vehicle can select the most energy efficient route because the human driver is entertained by the secondary task and minds less about slower accelerations, lower speed values and slightly increased travel time. Different ACC parameters and motion planning algorithms can result in different effects concerning fuel consumption. To assess these effects, 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, behavioral inputs can be evaluated and employed in following modeling studies, aimed at assessing the effects of different market penetrations and traffic control strategies or the impacts in the medium and long term.

VII. Conclusions and Future Activities

The scope of this paper is to characterize the most likely implementation scenarios concerning the L3 Highway Chauffeur system, focusing more on the probable impacts than the actual operational framework. Thus, once defined how an HC vehicle could behave on highways, the impact analysis was addressed towards two of the impact areas defined in [1]: Traffic Efficiency and Environment. To evaluate the system a set of research question has been derived and a first answer has been given, when possible, based on the current available literature. This work is framed in a wider activity within the C-Roads Italy project; following a similar approach and on the basis of a wider bibliographical study, the impact assessment has been carried out concerning also Safety and User Acceptance. Moreover, the jointed implementation of the Highway Chauffeur system and of the C-ITS services in the same four impact areas has been evaluated too. It should be highlighted how the Highway Chauffeur system is not yet a well-established reality and that many solutions or possibilities are being developed. Therefore, a qualitative approach was preferred but, nevertheless, indications about future research directions are provided. Every research question formulated in the previous paragraph should be analyzed for different levels of market penetration of the Highway Chauffeur system. The impact of different time gaps among the traffic flow should be evaluated though modeling works, possibly based on behavioral parameters recorded during field tests. The potentiality of V2X communications should be explored both referring to the tuning of the control parameters and to additional information provided by C-ITS services. Moreover, the impacts of the take-over transition should be assessed both through modeling works and especially field tests, on the basis of the most acknowledged solutions concerning HMIs and warning delivery strategies. Lastly, an extensive field test campaign should be carried out through the European countries to evaluate the interactions between HC vehicles and manually driven vehicles. An increased number of field tests should allow a comparison of the resulting impacts and, thus, grant the possibility to define a set of numerical values not bound to a specific system or OEM.

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