# Virtual Testing of Advanced Driving Assistance Systems

Maria Russo Spena, Francesco Timpone, and Flavio Farroni

***Abstract***— This paper presents some results on the development and testing of new solutions in the field of driving automation. The introduction of increasing levels of vehicle automation aimed at enhancing road safety requires a renewed approach to the research and development process and needs a multi-actor environment where the innovation can be tested. Indeed, vehicle automation spans several scientific disciplines and it is becoming exceedingly difficult and too costly for a single research innovation team to go in depth into all technologies and solutions. This is shifting the innovation process toward a multidisciplinary approach in which the only way to ensure an easy, rapid, efficient and scalable introduction of the required innovation is to adopt integrated and complex testing platforms for the simulation of automation solutions, based on a modular architecture, where independent components can be developed and then integrated and tested in a multi-actor environment. A platform for virtual testing is presented herein and employed to assess the performance of an integrated driving assistance solution based on computing appropriate surrogate measures of safety that allow for the transition between different automation logics in free-flow, car-following and emergency braking conditions.

***Keywords***— Intelligent Transportation Systems; Advanced Driving Assistance Systems; Autonomous Emergency Braking; Driving Automation; Road Safety; Driving Behaviour; Adaptive Cruise Control, Intelligent Speed Adaptation.

## I. INTRODUCTION

ADVANCED Driving Assistance Systems (ADAS) have been designed, developed and tested for several years, and the development of further devices is under way. ADAS are increasingly adopted under an active safety paradigm. Indeed, although innovation in the field of passive safety is yet to be implemented, its growth is likely to be outperformed by that of active safety, aiming to prevent collisions rather than mitigate effects. Every day on Europe's roads 71 people continue to die in traffic accidents, in which drivers are acknowledged to play a crucial role. It is generally estimated that around 90% of road accidents are correlated with human error.

Studies [1] carried out in the USA show that a large proportion of traffic accidents can be caused both by the driver's distraction or inadequacy with respect to the traffic conditions, and by the driver's incorrect interaction with primary and secondary driving commands or other on-board and personal devices. The driver's inadequacy is particularly dangerous when the vehicle cruises in a dense traffic stream and, as the traffic increases, can be exacerbated by increasing levels of inter-vehicle interactions. Errors and accidents also occur because of performance errors (like overcompensation, inappropriate directional control, etc.). Automated driving at different levels has the potential to reduce accidents by reducing the impact of the human factor [2], thereby contributing in the long term to the reduction in road fatalities [3]. The problem is also serious at intersections, with automation attempts being suggested for such cases ( [4], [5] ). Indeed, in the near future rapid development is expected of medium-to-high automated vehicles, a phenomenon which will be boosted by the spread of car fleets owned by big market players and used by drivers on the basis of a non-ownership approach ( [6] ). However, the more advanced the system is, the more complex the integration in the vehicle will be, and the overload of information to the driver can sometimes be unproductive. There are common concerns in the human factor community that ADAS may fail to alleviate the workload and can even introduce a new source of workload due to the need to attend to new tasks. Thus, ADAS need to be carefully tested before being implemented on vehicles ( [7] ). Moreover, they should not be seen (at least, not yet) as a substitute for drivers, but as a co-driver that does not exclude the driver from the control loop even if his/her direct involvement in an increasing number of driving tasks can be replaced by automation [8]. The driver should still be able to intuitively understand the logics of automated driving assistance [9]. This is even more crucial [10] when interaction between the driver and the automation is required, for example when the system acts as a pure warning facility and/or the driver has to regain control of the vehicle in the transition from automated driving to manual. In these events the well-known out-of-the-loop syndrome [11] can occur in the human interaction with automation, characterized by poor mental models, low reaction times, and low accuracy in vehicle control reclaim.

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The above argument does not mean that the potential positive impacts of automation should be left out of the equation; rather, full automation is a long-term objective [12] and the full benefits can only be gained in the long run. Potential benefits can be achieved by gradually shifting the main driving role from the driver to the vehicle. Moreover, for acceptance of increasingly higher levels of interaction and automation, we need to understand drivers' needs as well as possible reactions of the automated vehicle to both human and automatic driving control logics. This issue arises at an early stage in the development and deployment process, before the pre-commercial testing phase at which ADAS are commonly considered in the car-making process. Indeed, several paradigms (and formal procedures too) have been established for pre-commercial testing of automation/assistance solutions, targeting the deployment of advanced components. These procedures are employed by car-makers and tier-one suppliers and range from application of international standards (e.g. ISO) to National Highway Traffic Safety Administration (NHTSA) testing, and from OEM internal processes to European New Car Assessment Programme (EuroNCAP) tests. These involve car-makers at the deployment phase and do not take into account at an earlier stage the possible adoption of different solutions, technologies or different ways to integrate the technologies with the vehicle. At the earlier phases of development and adoption, car-makers and tier-one suppliers rely on different tests, many of which are implemented thanks to appropriate simulation platforms. In all cases, the test scenarios aim to assess system performance under different traffic conditions and/or different pre-defined manoeuvres. In these contexts the vision of the driver's role is too often just to solicit the system, and the driver's model is intended as the mathematical or procedural representation of such solicitations. The result is that testing scenarios lack realism in terms of simulation of second-order effects, which are those related to driver's reactions to solicitations. Our work aims to reverse the previous concept and to put the driver side-by-side with the vehicle at the centre of the car-making process. This enables ADAS testing in fully realistic scenarios, starting from the earliest stages of the development and adoption process, allowing the development of safer, more robust, efficient and widely accepted/adopted ADAS solutions.

However, such a holistic and driver-centric approach exacerbates the current trend that involves an increasing number of technical disciplines in the automotive process, making it exceedingly difficult and costly for a development unit to treat all related technologies and study all the consequences on the vehicle and on the driver but also on the traffic and on traffic propagation on infrastructures and networks. Indeed, different driving mechanisms interact in terms of flow propagation, which could impact on how the flow is propagated and on how the network has to be adapted ( [13], [14]) in order to take such effects into account. Indirect impacts cam have effect at a transportation-planning level too [15], as capacities and performances of infrastructures can be drastically changed and the trade-off between technological innovation and transportation supply management becomes a real option.

In such a context, the only way to ensure an easy, fast, efficient and scalable introduction into the market for the required innovation is to adopt an appropriate development and testing platform, based on a flexible architecture, where the (reactive) driver's model is central and independent components can be developed and then exploited in a multi-actor environment. A representation of this integrated platform is shown in figure 1 below.

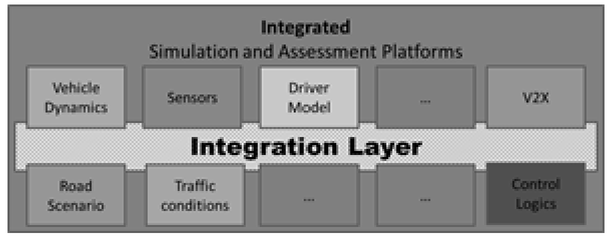


Fig. 1 – Integration platform

In this paper we present a first attempt to develop an integrated platform based on a multidisciplinary and modular approach. In section II the best-candidate platform is identified with respect to the desired characteristics. The critical issues in setting up the platform are verified and a second-best solution identified for this early stage of development. Two of the main modules of the platform, vehicle dynamics and the driver model, are considered and developed for use in ADAS design. In section III some general points are made on the development of driving automation and three ADAS solutions are identified, contextualized within the general automation framework, and designed to be integrated synergistically. In section IV the integrated ADAS solution is tested by means of the developed platform and the results presented and discussed.

## II. Simulation Platform

In order to allow for the necessary modular and multidisciplinary approach, the platform requires some particular characteristics. One of these is the integration layer; it should have an appropriate level of flexibility (and/or completeness) that allows the integration of different multidisciplinarily developed modules. Analysis of the available options steered our development towards adopting a driving-simulation environment, namely Scaner Studio, by Oktal [16], already installed on the car driving-simulation suite (two twin compact driving simulators and a high-fidelity dynamic one) at the University of Naples Federico II ( [17], [18]). Indeed, it is peculiar to professional driving simulators to possess a very sophisticated simulation environment for road scenarios and traffic conditions, as well as to reproduce driving feedback realistically (for instance with respect to steering and braking, [19]). Obviously, for all previous aims, a detailed representation of the vehicle dynamics is inherently required in driving simulations ( [20] ). In our case, the Oktal simulation environment is based on the Callas platform [21], [22], which allows for a detailed characterization of the vehicle dynamics. Callas software is a realistic simulator validated by car-makers (including PSA), and research institutions including IFSTTAR (formerly INRETS). The Callas model also takes into account vertical dynamics (suspension, tyres), kinematics, elasto-kinematics, tyre adhesion and aerodynamics.

Finally, the driving-simulation environment allows co-simulation, that is integration into the simulation environment of interacting control logics thanks to APIs developed in Matlab/Simulink.

The driving-simulation environment is our best-choice as an integration platform. Obviously, it requires the development and/or fine-tuning of a great variety of sub-models. Our choice here is to focus first on two such models: the vehicle dynamics and the driver.

Given the early stage of development of our platform and the chosen modules to be developed, a simpler integration platform can be employed. In particular, the Matlab/Simulink environment (that is contained in the Oktal platform) was used in this pilot work without loss of generality.

As a consequence, the development in the Matlab/Simulink environment of the driver model and the vehicle dynamic model is described below.

### *A. The driver model*

By driver model we mean the mathematical representation of the driver's reaction to stimuli from both the traffic and the driving assistance system. It is worth noting that at this early stage a driver model is used, but our (fully) integrated platform will allow interaction with the simulation of a real driver.

In this section we develop a driving model intended to simulate the reaction to a collision warning system (CWS). In our scheme, in car-following conditions the headway with respect to the leading vehicle can reach a value that activates the intervention of a CWS; the CWS warns the driver to focus on a potentially unsafe time-headway. Once the warning signal is raised, the driver's reaction can vary according to the actual headway with respect to the leading vehicle. In other words, if the warning signal is raised later (for shorter headways), the driver reacts more, while if the signal is raised very cautiously, the driver tends to react less or more slowly.

For the driver model, let:

- $H$ be the actual time headway with respect to the vehicle ahead, which can be computed as $H=sp/V_f = (\Delta x+L)/V_f$
- $V_f$ the actual speed of the vehicle;
- $sp$ the gross-spacing with respect to the vehicle ahead;
- $\Delta x$ the net spacing (measured bumper to bumper) with respect to the vehicle ahead;
- $L$ the length of the vehicle ahead, that can be approximated with average vehicle length;
- $fr$ the net spacing corresponding to the minimum headway, which can be fixed as an external parameter, for instance at the value of 1 m;
- $H_m$ the minimum vehicle headway that can occur during car-following trajectories, for very short transients and typically before overtaking takes place; it can be computed as $H=(fr+L)/V_f$
- $H_s$ the time-headway that is considered to be fully safe, that is the value that does not result in any stimulus to the driver. The stimulus is computed only for values of current headway that are less than $H_s$. Otherwise the stimulus is null; this value has to be computed by observation of driving styles and is dispersed across the population of drivers; it can also be considered to correspond to the threshold of perception of a slower vehicle ahead, according to the action point theory ( [23], [24], [25]);
- $ST$ the stimulus received by the driver because of the leading vehicle;
- $RP$ the probability the driver actually reacts to a warning raised by the assistance system, depending on the stimulus (ST);
- $RI$ the intensity of the driver's reaction, also depending on the stimulus (ST);
- $a$ the deceleration reaction the driver applies once he/she reacts to the stimulus;
- $a_{max}$ the maximum deceleration reaction the driver applies (here we fix a value of – 4 m/s$^2$);
- $a_{min}$ a minimal value for the deceleration reaction. Below this threshold the driver does not actually apply any deceleration (here we fix a value of – 0.5 m/s$^2$).

It is worth noting that the spacing can be measured by a forward radar mounted on the front of the vehicle, which is becoming an increasingly popular (and relatively cheap) device in automotive research. The other measurement required in real time is the cruising speed, which is a trivial measure supplied by the vehicle's on-board system.

Our model proposes to compute the stimulus with a logistic-type function as follows:

$$ST(h) = \left( \frac{1}{1+e^{-(2\alpha h-\alpha)}} - ST_{\min} \right) \cdot \frac{1}{(ST_{\max} - ST_{\min})} \tag{1}$$

where $\alpha$ is a modelling parameter to be estimated and $ST$ is a function of the actual headway $H$ via the standard headway $h$, defined as:

$$h = \frac{(H_s - H)}{(H_s - H_{\min})} \tag{2}$$

The equation for ST(h) gives standardized stimuli, in the range from 0 and 1. To this aim the maximum and minimum stimuli have to be computed, corresponding to the values of the (non-standardized) stimuli at the minimum (0) and maximum (1) standard headway (h):

$$ST_{\min} = \frac{1}{1+e^{\alpha}} \tag{3}$$

$$ST_{\max} = \frac{1}{1+e^{-\alpha}} \tag{4}$$

The probability of responding to a warning raised from the driving assistance system is also computed by using a logistic-type function:

$$RP(ST) = \left(\frac{1}{1+e^{-(2\beta\cdot ST-\beta)}} - RP_{\min}\right)\cdot\frac{1}{(RP_{\max}-RP_{\min})} \tag{5}$$

Once again, RP(ST) gives a standardized probability response, in the range from 0 and 1, and the values of the non-standardized response probability corresponding to the minimum (0) and maximum (1) standard stimulus have to be computed:

$$RP_{\min} = \frac{1}{1+e^{\beta}} \tag{6}$$

$$RP_{\max} = \frac{1}{1+e^{-\beta}} \tag{7}$$

The standard response intensity (RI) is computed as a function of the stimulus by using a logistic-type function as well. In this case not only are the minimum and maximum (non-standard) response intensity computed to properly scale the result, but the minimum standard intensity of the response ($\gamma$) is also fixed (it is assumed that if the driver reacts a minimum reaction intensity is attained). The equation for RI is:

$$RI(ST) = \left(\frac{1}{1+e^{-(2\delta\cdot ST-\delta)}} - RI_{\min}\right)\cdot\frac{1}{(RI_{\max}-RI_{\min})}\cdot(1-\gamma)+1 \tag{8}$$

where:

$$RI_{\min} = \frac{1}{1+e^{\delta}} \tag{9}$$

$$RI_{\max} = \frac{1}{1+e^{-\delta}} \tag{10}$$

Finally, the deceleration the driver applies in response to a warning raised by the assistance system depends on the probability of a response being applied times the intensity of this reaction; the resulting value (in the range from $\gamma$ to 1) is multiplied by the driver's maximum applicable deceleration ($a_{max}$ here fixed at the value |-4| m/s$^2$). It is also assumed that if deceleration is applied it is unlikely to be less than a minimum value ($a_{min}$ here fixed at |-0.5| m/s$^2$). In analytical terms:

$$a(h) = \max\left(a_{\min}, RP(ST(h))\cdot RI(ST(h))\cdot a_{\max}\right) \tag{11}$$

An example of the resulting function for the applied deceleration is depicted in figure 2 below, where the modelling parameters were fixed at $\alpha = 3$, $\beta = 2$, $\delta = 6$, $\gamma = 0.6$

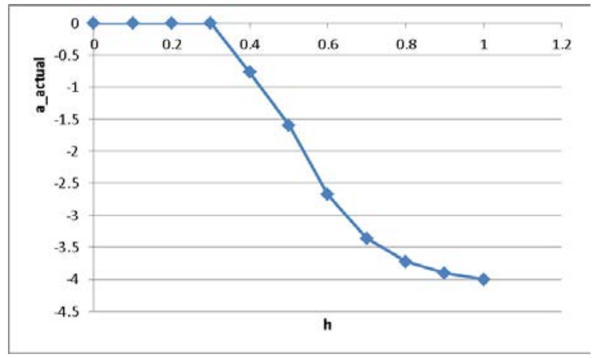


Fig. 2 – Results of the driver model

## B. *The model for the vehicle dynamics*

To carry out a more realistic simulation a vehicle dynamics model was coupled with the ADAS model. The purpose of the implemented vehicle dynamics model is to simulate, in real time, the vehicle's dynamic behaviour, thanks to continuous integration of the balance equations regulating the longitudinal and lateral vehicle motion.

In order to make the simulations as close to reality as possible, the implemented mathematical model also includes working dynamics for wheels, tyres, the engine and braking system, as well as a control system for automatic gearbox activation. Furthermore, a model able to provide an estimation of real-time fuel consumption of the vehicle in question is intended to be developed: such a model is embedded in the vehicle model discussed in the following, a further research purpose being the optimization of consumption performance during urban driving.

The model does not only involve vehicle dynamics, but it represents a general vehicle-behaviour model: besides the 'pure' vehicle dynamics equations, also the modelling of some other essential vehicle components (such as the engine, gearbox, braking system and others) was performed. In order to make the vehicle dynamics model clearer and more readable, it was organized into different sub-systems.

The main subsystem contains all the equations describing the vehicle dynamics: the Longitudinal Balance Equation, Lateral and Yaw Vehicle Dynamics and Vertical Load Determination, taking into account load transfers by means of the handling diagram/phase plane approach described in [26] and of the influence of roll stiffness [27]. In the input/output subsystem all the model's exchange parameters with the other subsystems and in particular with the ADAS model are suitably adjusted and displayed. In the I/O subsystem also the errors affecting the signals referring to the control variables are calculated, with reference to the target ones, so that the instantaneous error value can be deduced at any given time. Error determination is essential for the vehicle dynamics model, as this variable stands for the input signal controlling the processor units, designated to monitor the vehicle's behaviour and to make the decisions to adapt its working conditions to the desired ones (e.g. action of throttle and braking system). In the control unit subsystem the vehicle's real components and systems behaviour were introduced in order to make the final model as close to reality as possible. In particular, this subsystem allows introduction of the engine's dynamic behaviour, as well as the behaviour of the braking system, complete with an Antilock Braking System (ABS) unit. The ABS working principle is based on the wheels' speed detection (through dedicated sensors fitted on board), signal processing and a set of actuators directly operating the hydraulic braking system. The implemented ABS logic can be easily de-activated by simply operating on dedicated manual switches, specifically inserted in the model. Thanks to ABS logic, it is even possible to take into account the possibility of tyres locking, following the very intense application of braking and/or poor traction driving conditions (e.g. on snow, ice, rain etc.). As regards the variations in road frictional conditions, fundamental in ABS actuation, a specific physical grip model was employed [28]. In the ABS block two proportional-integral controllers were used to estimate the magnitude of the action to be performed on the vehicle's systems to let it move according to the ADAS control logics. The input signal for these controllers is the error magnitude, while the output signal is the action which has to be carried out in order to minimize the error itself. In the tyre subsystem, an essential part of the whole vehicle model, an evolved MF set of equations able to simulate wheel behaviour was introduced.

In this subsystem it is possible to determine the tyres' actual grip at any one time and to calculate the longitudinal and lateral interaction forces the tyre is able to perform. The above-mentioned interaction forces are the friction actions the tyres exert on the ground, depending both on the local friction coefficient inside the contact patch, strongly connected to fundamental thermodynamic phenomena observable at the tyre/road interface [29], [30], both on the vertical force acting on the tyre, hence even depending on the load transfer during vehicle handling. Knowledge of these forces is essential, since they deeply affect the vehicle's handling and road-holding: this means that these forces are intimately connected to vehicle safety, and hints at the importance of this subsystem and of the equations it aims to introduce.

## III. Driving Assistance Automation

Reconciling mobility needs with efficient and more sustainable transportation is a key objective that includes increased levels of road safety. Accident analyses have shown that human factors are responsible for up to 90% of road accidents [2]. Therefore, automatic driving systems (ADS) are considered one of the possible ways to reduce the road fatalities. Automation levels have been classified; for instance, as reported by ERTRAC [12], the Society of Automotive Engineers (SAE) considers six automation levels, ranging from 0 to 5. These approximately correspond to the five levels (from 0 to 4) established by the National Highway Traffic Safety Administration (NHTSA) [31], with SAE levels 4 and 5 corresponding to NHTSA level 4. Level 0 corresponds to no automation and level 5 to full automation. At automation level 1 (Driver Assistance) the vehicle is able to assist the human driver in some driving tasks related to both acceleration/deceleration and steering, but the main responsibility for monitoring the driving context is up to the driver, who is also in charge of fallback. At level 2 (partial automation) the vehicle accomplishes some specific driving tasks (both longitudinal and lateral driving), while monitoring and fallback are in charge of the driver. At level 3 (conditional automation) the vehicle executes driving tasks and monitors the driving environment. This applies to specific driving modes and the driver is required to resume the control in the case of fallback. At level 4 (high automation) the vehicle is responsible for all actions (including fallback) but this is applied to specific driving modes. At level 5 (full automation) the definitions of level 4 apply to all driving modes.

Various levels of driving automation have already started to be progressively introduced in the automotive arena [32]. Level 1 of automation has been widely applied for several years (e.g. adaptive cruise control, lane keeping assistance, etc.), level 2 systems have emerged (e.g. automated parking, adaptive cruise control with stop-and-go and/or truck platooning) and introduction of level 3 is now discussed (e.g. combination of adaptive cruise control and lane changing).

Here we present a combination of ADAS solutions that work synergistically. This approach allows the resulting integrated solution to be classified at automation level 3. The main idea is to define the field of application of each of these systems appropriately in order to ensure the most correct application of any of them and the most suitable transition from one to the other. Intelligent speed adaptation (ISA), advanced cruise control (ACC); collision warning system (CWS) and, finally, autonomous emergency braking (AEB) are applied according to appropriate surrogate measures of safety, evaluated at run-time. Moreover, the systems are applied in such a way that the driver perceives for most of the time (that is when the ACC runs) that the automation is human-like and consistent with his/her own behaviour. This ensures that the driver is always in-the-loop of the driving control process. The driver interacts with the automation system in the case of intervention of the CWS; in this event the driver's reaction is simulated by adopting the driver model described in section II.A. All control algorithms result in the need to apply accelerations and decelerations to the vehicle. These represent the stimuli viewed as from the vehicle (and not the driver). Application of these stimuli and the resulting effects on the vehicle are simulated with the support of the vehicle dynamics model described in section II.B.

### *A. Integrated Logic Control*

Integrated control logic is based on the run-time evaluation of headway (H) and time-to-collision (TTC), which are based on continuous measurement of the follower's speed and relative speed and spacing with respect to the vehicle ahead. TTC is computed when the relative speed, measured as the leader's speed minus the follower's one, is lower than zero, that is where the follower approaches the leader. It is the time after which a collision between the two vehicles will occur if the collision course and speed difference are maintained [33].

H and TTC can be computed at each instant by:

$$H=(\Delta x+L)/V_f \quad \text{and} \quad TTC=\Delta x/\Delta v$$

where, in addition to variables already introduced in section II.A, $\Delta v$ is the relative speed with respect to the vehicle ahead. The relative speed can also be measured by a forward radar. It is worth noting that H and TTC are also considered surrogate measures of safety [34] [35]. Hence they are appropriate to manage the transition between different solutions that are conceived for different safety-related conditions and tasks. The core of our integrated system is an ACC. Once activated, it allows the driver to set a desired cruising speed. This speed is maintained in free-flow traffic conditions until a slower vehicle ahead influences the controlled vehicle. From this point on, the vehicle runs in a car-following condition. If active, an ISA overrides the driver's desired speed and suggests to the ACC the speed posted by a digital map or by an I2V communication system. The need for the driver to regain control of the vehicle can be requested by the on-board CWS. Indeed, if for any reason, the headway (H) between the controlled vehicle and the vehicle ahead is below a critical threshold, the CWS asks the driver to re-establish conditions of greater safety. The CWS acts as a real safety assistant, monitoring unsafe headways and warning the driver to regain control of the vehicle; the driver model simulates the response to such a warning. Should not only the headway be below a given threshold but also the TTC decrease below another threshold, the danger is not only potential but also imminent. In this event, the reaction has to be as prompt (and intense) as possible, quicker than the perception and reaction time of the driver to the CWS warning. This is the role played by the AEB, which automates braking in order to avoid the incident or (more likely) to reduce impact, damage and injuries. The overall (integrated) control logic is depicted in figure 3 below.

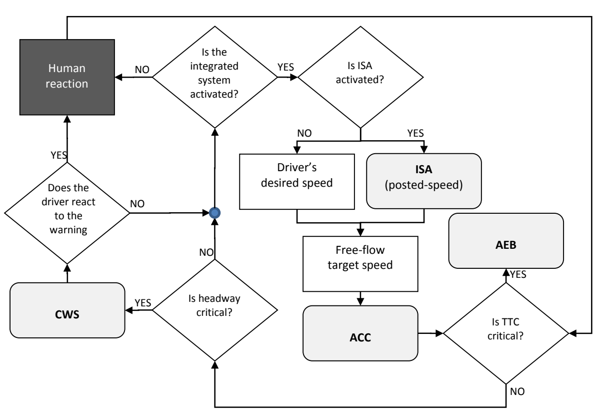


Fig. 3 - Integration logic

### B. Behavioural models for ADAS

The transition and integration across the different ADAS logics is ensured by the headway and TTC, as described in the previous subsection. Moreover, each single logic (ISA, ACC, CWS and AEB) potentially interacts with the driver. Logics for ISA and AEB do not involve the driver in an active role and interaction is very low or zero. Indeed, the posted speed of the ISA solution is applied by the vehicle automatically, no intervention is required by the driver and, assuming that the posted speeds are smooth and consistent, there are no particular issues to be addressed about the acceptability of such automation. In the case of ISA the interaction of the solution is with the vehicle (hence with the model developed in section II.B) rather than with the driver. In the case of intervention of the AEB the impact on the driver (and on the vehicle) is extreme but the interaction with the driver is very low; given the emergency conditions, the driver is completely excluded from the control loop of the vehicle, and regaining control over the vehicle (if at all, if the accident has been completely avoided) occurs after the vehicle has come a complete (or almost complete) halt. Interaction of the AEB with the vehicle (hence with the model of the vehicle dynamics) is intense and crucial. Another different aspect is the effect of AEB accuracy on the propensity of drivers to use the system without switching it off. It is evident that unreliable AEBs (e.g. which have a high rate of false alarms) induce drivers to deactivate the solution. However, such a long-term interaction is not of a run-time type.

Events that strongly interact with the driver are the intervention of the CWS and the running of the ACC. As regards the CWS, the driver model described in section II.A allows for simulating the driver's interaction with the system, thus enabling the logic to be tested in a virtual environment. With regard to the ACC, the logic to be applied by this system has to be specified. It is worth noting that an appropriate logic is required, which avoids any undesired effect in terms of safety. It has been shown elsewhere that in the case of highly automated solutions the reduced ability of the driver to regain control of the vehicle in the event of failure of the automatic system entails a high risk [36]. Indeed, even with moderate automation, as in the case of ACCs, drivers could experience problems regaining control, perhaps because of overreliance on vehicle systems and/or reduced situational awareness (SA) [37]. In order to avoid reduced SA, the ACC logic here employed was designed according to the human-like approach described in [38]; other approaches to human-likeness for driving skills can be found in [39]. Human-likeness is ensured by an on-demand calibration process of the parameters of the linear model, assumed to take place while the driver still has full control of the vehicle. Indeed, during the control-learning phase the driver actually drives the car and the ACC observes his/her behaviour. A run-time calibration procedure is able, during the learning phase, to translate the observed behaviour in terms of parameters of a linear stimulus-response model. Once the model is calibrated, the sampler ends the learning phase and switches to the running phase; it takes control of the vehicle and activates the identified behaviour. The learning-running approach has been shown to be feasible in [38] and [40], where the linear stimulus-response model has been validated with respect to both synthetic (laboratory-generated) and real-world observed car-following trajectories.

## IV. USING THE PLATFORM

The simulation platform was validated by:

- comparing driving trajectories simulated by the platform with real-world observed trajectories; this validates the virtual testing framework with respect to its ability to reproduce real data;
- analysing the driving trajectories in the case of adoption of the integrated ADAS logic and assessing consistency with expectations of the simulated results.

As the simulation platform integrates the driver model (section II.A), the model of vehicle dynamics (section II.B), and the behavioural ACC model (section III.B), validation was carried out with reference to the integrated performance of these models, without trying to separate the impacts or validate the modules separately.

Figure 4 below shows the accordance of a simulated vehicle trajectory with an observed one; as the vehicle is mainly in car-following conditions, the ACC logic and the model of the vehicle dynamics are most important in terms of modelling accuracy. Accuracy in terms of spacing is much more critical than that in terms of speed, as an effect of integral errors.

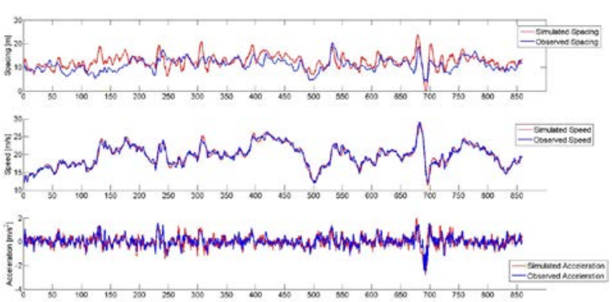


Fig. 4 – Modelling accuracy

Figure 5 below shows the result in terms of activation of the CWS and AEB logics. Some interventions of the CWS can be highlighted; these occur when the spacing with respect to the vehicle ahead is excessively reduced. Analysis of the decelerations suggests that the second of the first two (very close) warnings results in a reaction on the part of the drivers. Differently, after more than 300 seconds of simulation a warning raised by the CWS remains unheard, and as a consequence the AEB is invoked, with a sudden intense deceleration. Data replicates the initial condition and the boundary conditions of an observed car-following trajectory. In the observed data the ADAS are not in place. However, the ADAS interventions cause only local divergence of the simulated trajectory with respect to the observed one. Once again, the fitting is very satisfactory. Importantly, the trajectory of vehicle speed (as well as that of acceleration) is smoother (apart from AEB intervention) in the simulation than for the observed data; this is an encouraging property for integrated control logic.

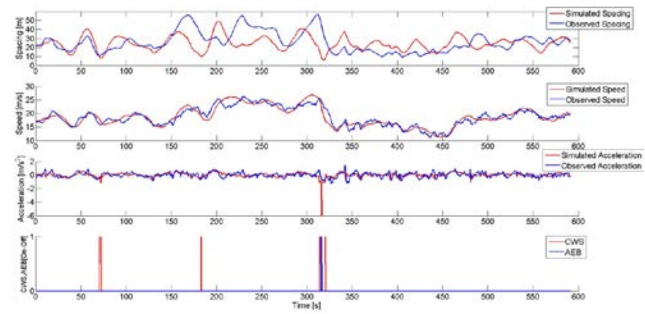


Figure 5 – Activation of CWS and AEB

Figure 6 below shows another case in which a very aggressive driver is observed. For this driver (as for all others participating in our experiments) the parameters of the ACC logic are calibrated thanks to a short learning phase. The aggressiveness of the driver is well captured by the model and the simulation replicates it, with the need of frequent (sometimes neglected) interventions by the CWS. Analysis of the acceleration plot shows several small decelerations (CWS activation and – in many cases – driver's intervention) and one intense deceleration. In this case the smooth speed and acceleration profiles activated by the ISA and the ACC are biased by the frequent decelerations imposed by the safety logics (CWS and AEB).

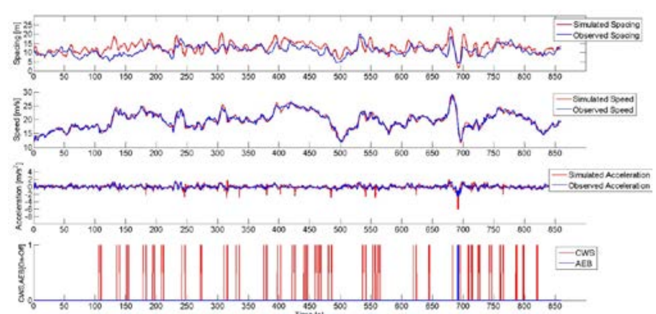


Figure 6 – Activation of the ADAS logics for an aggressive driver

## V. CONCLUSION

A platform was described and tested, allowing integration of different simulation models developed by specialists in a cooperative multi-actor environment. Two modules of the platform received particular attention in terms of development: the driver's model and the model of vehicle dynamics. Simulations were carried out, corresponding to real-world observations mainly collected during the DRIVE IN$^2$ project ( [41] [42]). The system works as expected, conditions of potential and imminent danger are eliminated, but the implemented driving behaviour is very similar to that which real drivers would have applied. An increase can be observed in road safety with an (integrated) control strategy that is likely to maintain the driver within the control loop of the vehicle. It is confirmed that the ACC behaves human-likely. If used alone, it induces few situations of potential danger, but a significant number of imminent dangerous situations (in a few cases up to the collision, with almost null TTC values). This is consistent with the proposed ACC, which does not embed a safety logic that is left to the CWS and the AEB. The behaviour learned by the ACC is always applied. In some conditions this means that (transient) drivers' aggressive behaviours are moderated by the ACC (few potential dangers), while in other conditions (typically, rough braking of the vehicle ahead) the ACC underperforms with respect to the human driver who would have promptly modified his/her behaviour in order to avoid potential or imminent danger conditions. Of course, these potential and imminent danger conditions, not dealt with by the ACC, are recovered once the CWS and AEB are considered.

In the future, further analyses should be devoted to acceptability among drivers of the integrated system. This can be properly done by supporting the integration of testing procedures in a driver-in-the-loop (DIL) approach, based on the driving simulator. This could also allow the system to be tested with the real perception and reaction times of the drivers with respect to CWS warnings, as well as with observed imposed decelerations.

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