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Real-time Performance and Safety Validation of an Integrated Vehicle Dynamic Control Strategy

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Abstract: The state of the art in automotive control has proposed several analytical, simulation and experimental studies of longitudinal adaptive cruise control strategies, and of lateral control strategies. However, methodical integration of these two strategies is to a large extent missing, as well as validation in real-time computing environment of the safety and performance of longitudinal and lateral integrated solutions. This work proposes a real-time validation of an integrated vehicle dynamic control strategy, designed to create safe interaction between longitudinal and lateral controllers: the integrated system is designed, implemented and tested through Dynacar, a real-time simulation environment for the development and validation of vehicle embedded functionalities. The results show that the proposed integrated controller satisfies the performance in terms of real-time computation, path tracking and collision avoidance for various driving situations.

Keywords: longitudinal and lateral vehicle control, vehicle system integration, real-time validation, advanced driver assistance systems.

1. INTRODUCTION

Advanced vehicle control systems should use environment sensors (e.g. radar, laser, vision, GPS) to improve driving comfort and traffic safety by assisting the driver in recognizing and reacting to potentially dangerous traffic situations (Gietelink et al. (2006)). To improve handling performance and active safety of vehicles, a considerable amount of control systems for vehicle lateral dynamics and longitudinal collision-safety has been developed and utilized commercially over the last two decades. The most notable are Cruise Control (CC), Adaptive Cruise Control (ACC), Collision Avoidance (CA), Vehicle Stability Control (VSC), which have been extensively researched Cho et al. (2011). However, the vast majority of systems proposed in literature (Reschka et al. (2012); Shakouri and Ordys (2014); Moon et al. (2009); Eyisi et al. (2013)) addresses the task of longitudinal control with minimal or no focus on integration with lateral control. As a result, the major drawback of commercially available longitudinal control systems is limited performance in cornering situations, where the road presents current/future curvatures (Shakouri and Ordys (2014)).

The situation with lateral control is complementary, in the sense that some systems have been proposed, but with limited integration with longitudinal strategies, especially in collision avoidance scenarios. Lateral controllers can be of vehicle-following or of path-tracking type. Most studies on lateral control focus on lateral control of one single vehicle (Gehrig and Stein (1998); Taylor (1999); Goi et al. (2010)), with a few studies on vehicle platoons (Papadimitriou and Tomizuka (2004); Khatir and Davison (2005)). In fact, not all proposed strategies are suitable to control the lateral dynamics of a vehicle platoon. The most evident example is cutting the corner of a preceding vehicle, which might become a serious problem when vehicle platoons are considered (Solyom et al. (2013)). For this reason, path-tracking type strategies have become more popular, notwithstanding that integration with longitudinal strategies is also not addressed (Hingwe and Tomizuka (1998); Abdullah et al. (2006); Kang et al. (2008)). In this work we will consider a path-tracking controller with feedforward based on the curvature of the reference path.

Since the vehicle longitudinal and lateral motions are naturally coupled, it is recognized that the integration of longitudinal and lateral ACC is necessary to obtain both lateral stability and safe clearance of autonomous driving vehicle, and also to avoid rear-end collisions in severe driving situations (Cho et al. (2011)). However, integration presents some challenges due to the co-existence of several control subsystems that can cause increased complexity and possible conflicts of control actions (Attia et al. (2014); Nilsson et al. (2016)).

In this paper, a real-time performance and safety validation of an integrated longitudinal and lateral control

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strategy is performed. In particular, in severe driving situations, the control action is computed based on longitudinal and lateral indexes for driving situations to coordinate the brake and steering actuators. Simulations are conducted in Dynacar RT (Tecnalia Research & Innovation Foundation (2016)), a real-time simulation environment for the design, development and validation of vehicle systems or subsystems. A set of different traffic scenarios which are likely to occur in reality is used for this study.

The rest of the paper is structured as follows; Section 2 introduces the stand-alone longitudinal and lateral controllers, while the integrated design is discussed in Section 3. Section 4 explains the main features of the Dynacar software. Simulations for the evaluation are conducted in Section 5 and finally conclusions regarding the work are presented in Section 6.

2. STAND-ALONE LONGITUDINAL AND LATERAL CONTROLLERS

Stand-alone longitudinal ACC refers to a conventional system in which only longitudinal control is considered. Stand-alone lateral vehicle control only involves the steering of the vehicle. The two strategies used in this study are explained hereafter.

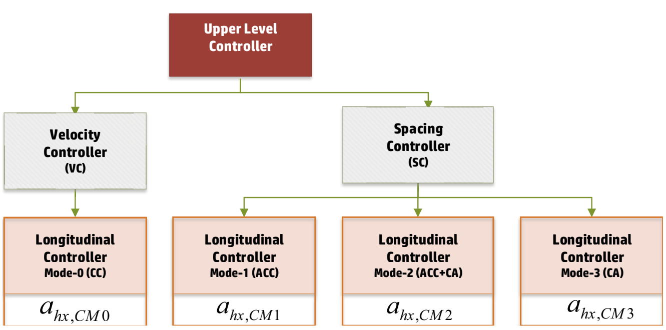

Fig. 1. Control modes of longitudinal controller

2.1 Longitudinal controller

The longitudinal controller, aims to maintain the longitudinal motion of the vehicle (CC, ACC, ACC+CA, and CA functionalities, as depicted in Fig. 1). The CC functionality is achieved via a proportional-derivative (PD) controller that determines the acceleration $a_hx, CM0$ (Shakouri and Ordys (2014)). The ACC functionality is achieved via a Linear Quadratic (LQ) controller which controls the acceleration of the vehicle to keep the host vehicle at the desired distance d_{des}

The functionality is further augmented, similar to that of Moon et al. (2009), via an index-based control law which schedules the acceleration ($a_{h_x,CM1}$, $a_{h_x,CM2}$, and $a_{h_x,CM3}$) and defines three functions: ACC, ACC+CA and CA, respectively. The switching from one function to another is determined by a combination of a warning index $f_1(\kappa)$ and an inverse time to collision index $f_2(TTC^{-1})$. Note that other longitudinal indexes are possible and have been proposed in literature (Russo et al. (2016)). Here, the switching is not dependent in any way by the lateral dynamics.

2.2 Lateral Control Design

The lateral controller is based on a linear model of the lateral position error, yaw angle error, rate of change of the lateral position error and rate of change of the yaw angle error (Gehrig and Stein (1998)). This model is obtained by linearizing the tire forces and substituting them in the classical bicycle model dynamics (Rajamani (2012)).

The steering control input $\delta_{f,des}$ is chosen as front wheel steering angle. Following a similar approach as in Taylor (1999); Kang et al. (2008), a combined feedback and feedforward control is used to develop a steering controller, where the feedforward control input is computed using the curvature information within the preview distance. As a result, the steering control input is computed as

$$\delta_{f,des}(t) = \delta_{f,FB} + \delta_{f,FF} \tag{1}$$

where $\delta_{f,FB}$ is a state feedback from the state of the linear model, and $\delta_{f,FF}$ is a feed-foward term using the road information between time t and $t + T_p$, and T_p is the preview time.

Note that the stand-alone lateral controller does not take into account any limit on longitudinal speed (which is essential so that the lateral acceleration of the host vehicle does not exceed a critical value in order to improve the safety of lateral vehicle behavior). The integration between longitudinal and lateral controller will be explained hereafter. For lack of space, only the main ideas are presented, together with some references to support the usage of these controllers: the interested reader can consult the extended version of this work (Idriz et al. (2016)).

3. INTEGRATED CONTROL DESIGN

In this section, the previously designed longitudinal and lateral controllers are integrated into an Integrated Vehicle Dynamics Control (IVDC), shown in Fig. 2. The proposed

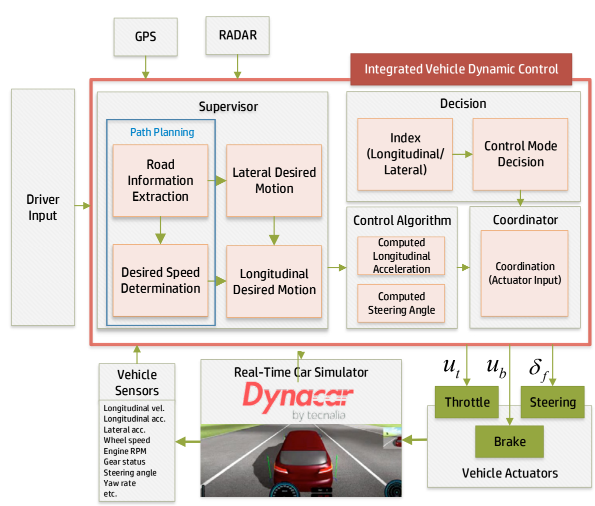

Fig. 2. Scheme of multi-layer integrated vehicle dynamics control system

controller consists of four components: Supervisor, Decision, Control Algorithm and Coordinator.

3.1 Supervisor

The supervisor determine the desired velocity of the host vehicle $\upsilon_{h,des}$ based on road information, driver's input, and human comfort:

$$\left|a_{h_{y,des}}(\upsilon_{h_x})\right| = a_{y,0}(1 - \frac{\upsilon_{h_x}}{\upsilon_{h_{max}}})$$
$$\upsilon_{h,comfort} = \sqrt{\rho\left|a_{h_{y,des}}(\upsilon_{h_x})\right|}$$
$$\upsilon_{h,set} \leq \upsilon_{h,limit} = \sqrt{\rho g \mu} \quad (2)$$

$$\upsilon_{h,des} = \begin{cases} \upsilon_{h,set} & \text{if} \quad \upsilon_{h,set} < \upsilon_{h,comfort} \\ \upsilon_{h,comfort} & \text{if} \quad \upsilon_{h,comfort} \leq \upsilon_{h,set} \end{cases} \quad (3)$$

where $\upsilon_{h,set}$ is the user-set velocity of the host vehicle, $a_{y,0}$ an acceptable medium comfort-level lateral acceleration constant (Xu et al. (2015)), $a_{h_{y,des}}$ is the desired lateral acceleration of the host vehicle based on human comfort, $\upsilon_{h,comfort}$ is the maximum velocity of the host vehicle giving comfort in curve (Kang et al. (2008)), μ is the friction coefficient, g is the gravitational acceleration, $\upsilon_{h_{max}}$ is the maximum speed of the host vehicle in term of mechanics, $\upsilon_{h,limit}$ is maximum allowable velocity in curve in order to create safe lateral vehicle behavior by means of keeping the vehicle on the road without being driven away from the curve.

3.2 Decision

A task of the decision layer is to determine the upper-level control mode based on the index-plane using longitudinal and lateral indexes. Fig. 3 shows the proposed index-plane. The index-plane consists of a Normal Driving Mode, an Integrated Safety Mode I, and an Integrated Safety Mode II. Integrated safety modes are used to cope with collision and unstable lateral motion of the vehicle. Similar to Cho et al. (2011), the longitudinal index $I_{longitudinal}$ is determined by using a warning index and an inverse TTC. In this work we propose a novel lateral index ($I_{lateral}$) based on experimental studies on human driving (Xu et al. (2015)), where the absolute value of lateral acceleration is limited via velocity-dependent constraints

$$a_{ymax}(\upsilon_{h_x}) = \mu g(1 - \frac{\upsilon_{h_x}}{\upsilon_{h_{max}}})$$
$$I_{lateral} = \frac{\left|a_{h_y}\right|}{a_{ymax}(\upsilon_{h_x})} \quad (4)$$

where a_{h_y} is the lateral acceleration of the host vehicle and a_{ymax} is velocity-dependent maximum value of lateral acceleration. The idea behind Figure 3 is that the longitudinal index exceeds unit, the danger of collision is high; if the lateral index exceeds unit, the danger of unstable lateral motion is high. Note that in the "Integrated Safety Mode I", the longitudinal safety control has priority to avoid rear-end collision; while in the "Integrated Safety Mode II", the lateral stability control has priority to improve vehicle lateral motion.

3.3 Control Algorithm

Control algorithm respectively calculates:

- The desired longitudinal acceleration as in Section 2.1.

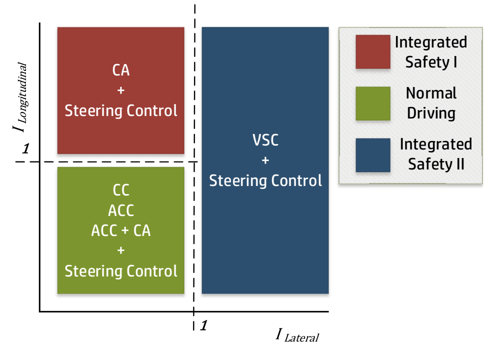

Fig. 3. Control modes in the index-plane

- The desired steering angle as in Section 2.2.

Note that "Normal Driving Mode" as shown in Fig. 3 covers CC ($a_{hx,CM0}$), ACC ($a_{hx,CM1}$) and ACC + CA ($a_{hx,CM2}$), while "Integrated Safety mode I" covers CA ($a_{hx,CM3}$). In Normal Driving Mode, longitudinal acceleration $a_{hx,des}$ is determined as $a_{hx,CM0}$ or $a_{hx,CM1}$ or $a_{hx,CM2}$ respectively depend on either velocity control or spacing control mode. In Integrated Safety Mode I, calculation of longitudinal acceleration is constrained using the Kamm circle equation $\sqrt{F_{y_i}^2 + F_{x_i}^2} \leq \mu F_{z_i}$ (Rajamani (2012)).

In Integrated Safety Mode II, the VSC system has priority in order to improve vehicle lateral motion and keep the vehicle in the desired path. VSC calculates a desired longitudinal acceleration from physical limitation in braking with cornering situation.

Physical limitation can be induced from tires to whole vehicle with the Kamm inequality. Then, the desired longitudinal acceleration $a_{h_{x,des}}$ can be derived as

$$a_{h_{x,des}} = -\frac{\sqrt{(\mu m g)^2 - (\sum F_y)^2}}{m} \quad (5)$$

where m is the total mass of the vehicle, g is the gravitational acceleration. The idea of this extra constraint is to couple the longitudinal and lateral dynamics in a safe way, as demonstrated in the evaluation section.

3.4 Coordinator

Based on the desired longitudinal acceleration and steering angle, the coordinator manipulates throttle and brake input (u_t or u_b respectively) via the low-level controller designed in Dynacar, and the steering angle (δ_f) input through the steering actuators.

4. THE DYNACAR ENVIRONMENT

In order to validate safety and performance of the proposed control in a realistic scenario, a vehicle simulation software is used. Since the investigated IVDC has ideally to be implemented in actual vehicles, it is of fundamental importance to adopt Real-time (RT) computing, to allow for testing in close-to-real-world situations. RT itself means that the correctness of the simulation behavior depends not only on the logical results of the computations, but also on the physical time when these results are produced

(Popovici and Mosterman (2012)), therefore aspects like computational speed and synchronization of events are crucial.

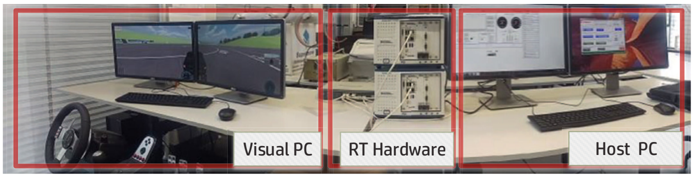

Fig. 4. Dynacar Setup

In this work, validation of IVDC is performed via real-time vehicle-in-the-loop simulation environment Dynacar RT by Tecnalia Research & Innovation Foundation (2016). Dynacar RT provides validated and interchangeable vehicle model (Pena et al. (2012)) and works in conjunction with Veristand (National Instruments Corporations (2014)). Veristand platform is used to run the control algorithm and perform the simulation result logging. The configuration consisted of NI PXIE-8880 Embedded Controller running the Dynacar RT and controller algorithm under PharLap ETS Real-Time OS, connected to data logger PC (Host PC) in one side and PC that provides visual feedback of the vehicle simulation on the other side (Visual PC). Refer to Fig. 4 for the setup configuration.

The control architecture is first designed offline in MATLAB/Simulink. The Simulink model is generated to C code and subsequently compiled as Veristand model binary. The resulting code will run in real-time platform in parallel with Dynacar RT. Fig. 5 shows the overall system architecture.

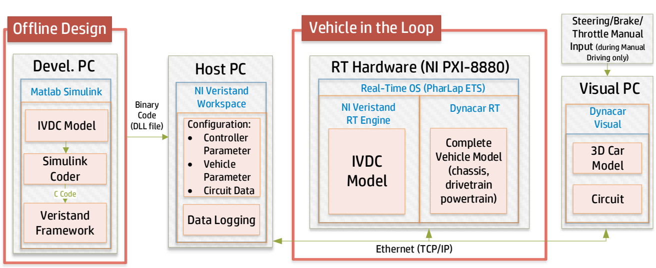

Fig. 5. System Architecture

The proposed IVDC is designed to run at 100 Hz, a rate often used for control loops in automotive applications and vehicle dynamics application (Popovici and Mosterman (2012)). The reference development platform for control architecture design is a Workstation-class Notebook (HP ZBook 15 G2) which is equipped with Intel Core i7 4710MQ Processor. Note that for this study the term real-time is appropriate since the target platform (NI PXI-8880 with Intel Xeon E5-2618L v3 processor) is the same platform that has been installed in the actual testing autonomous vehicle at TU Delft.

The vehicle model used in the testing is based on the integration of virtual rolling chassis formulation to independent steering, braking, powertrain and brake model which results in full vehicle model (Pena et al. (2012)). An SUV-class vehicle model with 6-speed automatic transmission is used throughout the simulation. The full vehicle parameter can be found on Table 1.

Table 1. Vehicle Parameters

Parameters	Value
Vehicle mass	1.870×10^{3} kg
Coefficient of rolling resistance	0.035×10^{-2}
Coefficients of the Pacejka model (dry asphalt) $\mu(s_i) = D_P \sin(C_P \arctan(B_P s_i - E_P(B_P s_i - \arctan(B_P s_i))))$	$B_p = 1.000 \times 10^{0}$, $C_p = 1.900 \times 10^{0}$, $D_p = 1.000 \times 10^{0}$, $E_p = 9.700 \times 10^{-1}$
Distances of front wheel axle from CoG	1.400×10^{0} m
Distances of rear wheel axle from CoG	1.620×10^{0} m
Height of CoG	4.500×10^{-1} m
Mass moment of inertia w.r.t vertical axis	4980×10^{3} kg m^{2}
Steering actuator dynamic constant	2.000×10^{-1}
Steer to drive wheel ratio	1.250×10^{1}
Cornering stiffness	1.665×10^{4} N rad^{-1}

A virtual track of 1000 m length is designed to reflect real-life highway road. The regulation and standard of highway roads varies by countries, however majority of EU countries use lane width of 3.75 m, which is used as parameter of the track. Furthermore, in order to evaluate the lateral control performance, the track present curve with 580 m radius. This radius is in accordance to most EU countries standard of minimum curvature radius required for highways with a design speed of 100 km h^{-1} (Wegman (1998)). Additionally, the surface static friction coefficient μ_s is set to 0.9 to reflect dry tarmac. The realization of the designed track can be seen in Fig. 6.

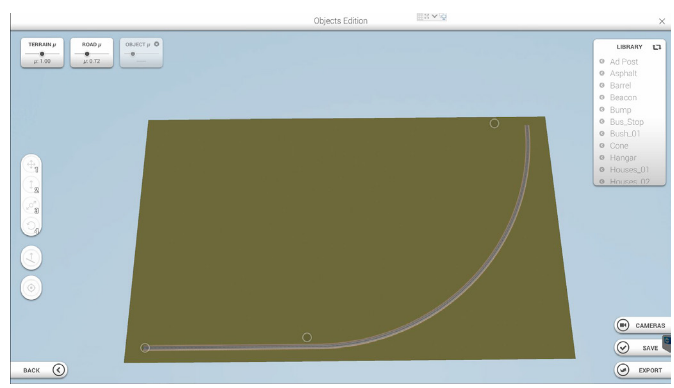

Fig. 6. Track Realization

5. EVALUATION

The integrated control system is evaluated by running two test scenarios which are intended to simulate unsafe driving situations. In the first scenario, the Integrated Safety I mode is activated to prevent rear-end collision. In the second scenario, the Integrated Safety II mode is activated to handle unsafe lateral motion induced by external forces. All scenarios run in the track shown in Fig. 6, i.e in cornering situations where longitudinal and lateral integration is crucial. The performance specifications can be seen in Table 2.

Table 2. Performance Specifications

Variables	Criteria
$\lvert v_{h,error}\rvert$	≤ 1.0 km h^{-1}
$\lvert d_{error}\rvert$	≤ 0.5 m
$\lvert v_{rel,measured}\rvert$	≤ 3.6 km h^{-1}

Variables	Criteria
$\lvert y_r\rvert$	≤ 0.3 m
$\lvert \varepsilon - \varepsilon_d\rvert$	≤ 1.0 deg

5.1 Integrated Safety I

The results of this scenario are shown in Fig. 7. In this scenario, target vehicle decelerates at 3 s during cornering. Based on the current value of warning index and the inverse TTC, the integrated controller on the host vehicle detects unsafe situation and applies braking in order to avoid collision with the target vehicle. After 20 s, the target vehicle starts to re-accelerate. The controller accordingly makes the host vehicle accelerate while satisfying the spacing policy: note that longitudinal safety control has priority in the current driving situation in order to avoid rear-end collision (note the large deceleration of about $-8\,\mathrm{m\,s^{-2}}$ to avoid collision).

Finally, this scenario reveals that during the collision avoidance, lateral stability control is simultaneously maintained by manipulating the steering angle.

5.2 Integrated Safety II

In this scenario, the lateral safety control performance is tested by inducing unstable lateral motion, which in reality can occur due to uneven road, severe weather condition or even side-collision with another vehicle. In Dynacar RT, unstable lateral motion is induced by adding external lateral force to the tires with total magnitude of 3600 N between 3s and 4s. Fig 8 shows that the vehicle is forcibly moved sideways for 1.2 m and the disturbance immediately causes the lateral index to exceed unit level and the integrated controller evaluates the current driving situation as unstable lateral motion for host vehicle. On this unsafe situation it can be seen that steering input is simultaneously applied to the vehicle along with brake to track the desired path while maintaining lateral stability.

Furthermore, the magnitudes of lateral position and yaw angle errors are within the predefined specifications. Overall, the integrated controller shows adequate handling of unstable lateral vehicle motion in a timely manner. A more complete overview of the simulations can be found in the demonstration video (Abdul Rachman and Baldi (2017)).

6. CONCLUSION

A real-time validation of an integrated control system has been presented. The integrated controller has been implemented in a Dynacar environment and simulations have been conducted in order to investigate the performance of the proposed integrated system in various driving situations. From the simulations, it has been shown that the integrated controller which coordinates both longitudinal and lateral motions augments the safety of vehicle in severe driving situation.

Future work will follow both theoretical extension and implementation: from a theoretical point of view it is important to obtain formal stability guarantees, possibly using the tools of switching control (Baldi et al. (2012, 2014b)). Even more important is to develop multi-modal adaptive control (Baldi et al. (2014a)) with the capabilities to control changes in the vehicle and in the environment. With formal stability guarantees it would be interesting to see how an improved coordinated control scheme performs on icy roads where the coordination of lateral and longitudinal dynamics controls is more important. Ongoing work is the experimental verification of the integrated controller on test vehicles available at the Delft University of Technology.

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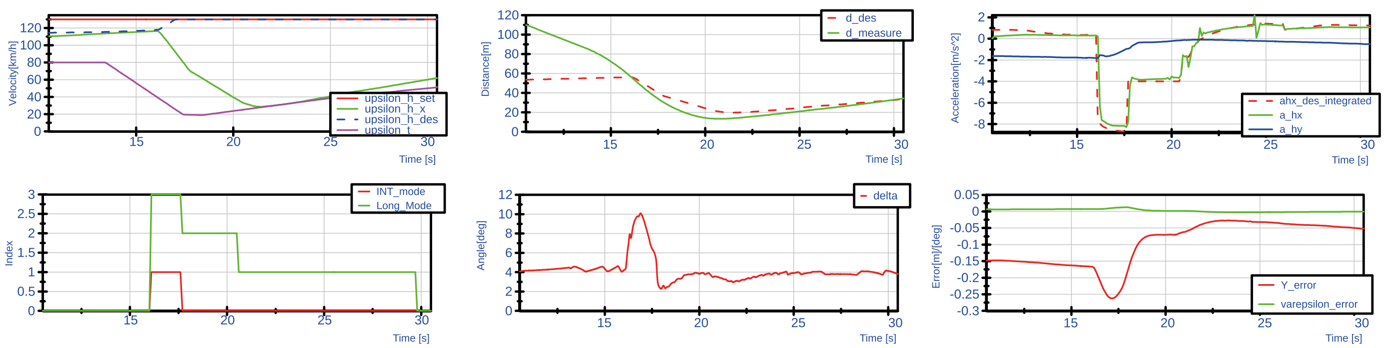

Fig. 7. Simulation results for Integrated Safety I
(top-left: longitudinal velocities, top-center: longitudinal distances, top-right: longitudinal and lateral acceleration, bottom-left: integrated and longitudinal controller mode, bottom-center: steering angle, bottom-right: lateral and yaw error)

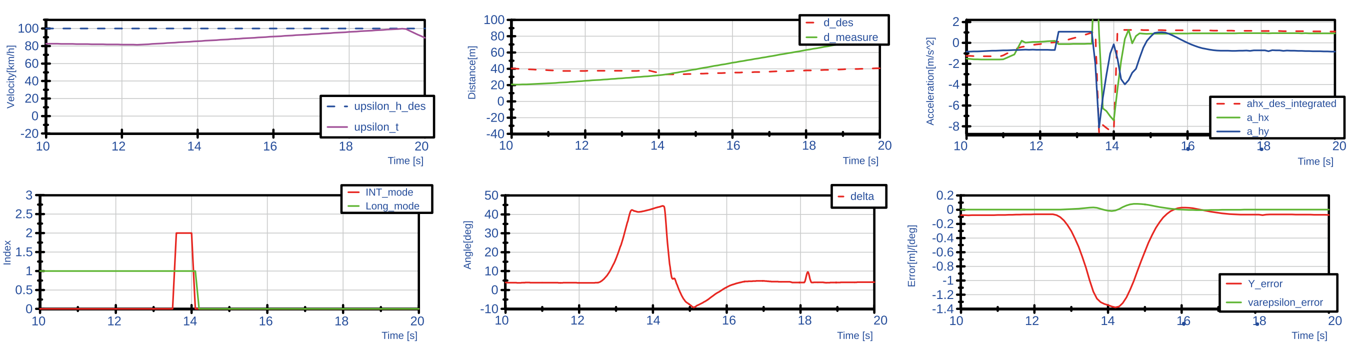

Fig. 8. Simulation results for Integrated Safety II
(top-left: longitudinal velocities, top-center: longitudinal distances, top-right: longitudinal and lateral acceleration, bottom-left: integrated and longitudinal controller mode, bottom-center: steering angle, bottom-right: lateral and yaw error)

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