Empirical Testing of Automotive Cyber-Physical Systems with Credible Software-in-the-Loop Environments

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***Abstract*—Automotive cyber-physical systems are constantly increasing in complexity, especially due to innovations like sophisticated advanced driver assistance features. The increase in system complexity, in turn, gives rise to complex distributed software which creates challenges for verification. Front-loading tests that are regularly performed in prototype vehicles or Hardware-in-the-Loop (HiL) to simulation and Software-in-the-Loop (SiL) environments can be used to validate design decisions and to significantly reduce overall development costs. Novel Automated Driving features, and the Open Context problem, however, move the challenge from the state-to-the-art to a knowledge problem (know-what instead of know-how). The ISO/PAS 21448:2019 for Safety of the Intended Functionality (SOTIF) acknowledges this change but no guidance is provided to the industry to making verification processes ready for operating vehicles in an Open Context environment that may require functional changes during the useful life of a vehicle. Since verification with HiL or vehicles will be all but impractical, in this paper we provide insights into the design of credible SiL environments that address functional and non-functional verification and validation concerns of software related automotive system in a continuous life-cycle. With the help of a use-case we demonstrate the significance of the novel approach compared to traditional automotive industry methods.**

***Index Terms*—software-in-the-loop, hybrid simulation, automotive CPS, credible simulation, system and software testing, virtual ECU.**

I. Introduction

Pressure on lead time and reduction of development cost is strong motivation for replacing hardware prototypes by simulation (e.g. SiL testing of ESP®- the Electronic Stability Program [1]). As the current trend in automotive industry is moving towards Automated Driving Functionality (ADF) and Advanced Driver Assistance Systems (ADAS), the role of simulation to address the validation of these complex cyber-physical automotive systems is constantly increasing. The problems associated with defining a valid model for deduction of functional requirements [2] gives rise to methodological questions formerly unknown to the automotive industry.

One solution approach is the separation of functional validity concerns from well established functional safety processes. In the latest ISO/PAS 21448:2019 standard for Safety Of The Intended Functionality (SOTIF) [3] the approach for the former problem can be categorized as:

1) consensus about functional models of environment, behavior and sensing performance
2) credibility through falsifiability and commitment to improvement

The satisfaction of the first category, i.e., to reach a consensus about the functional models, depends on various aspects, such as institutionalization, field observations [4], management and configuration [5]. Those aspects for a reliable consensus are essential for a separation of concerns in a tiered industry, and a standardization is on its way [5]. Category 2, the aspect of credibility, is a methodological and organizational problem that extends into the separation of concerns between functional and non-functional (e.g. technical) fields. Here, it is important to create a reactive (i.e. agile) socio-technical framework, that is well beyond of what is viable in the current framework of liability and recall where the effort for rolling out feature changes that fall in the domain of functional safety or other non-functional properties, is very high. To be "credible", however, the roll out of required updates must be fast and safe.

Today, model and simulation based engineering is encountered in all phases of the automotive product development cycle (as shown in Fig. 1) with specific requirements and roles for each integration level. Nevertheless, compared with the telecommunication or the software industry, where continuous life cycle is common, the automotive industry is not well prepared for a transition from verification and validation of

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non-functional properties in ”phase oriented” life cycle to a continuous life cycle. Further, the capability to roll out updates in the field, like in the telecommunications industry, increases the size of the security attack surface [7]. While increased security demands can be managed partially by careful architectural design, at least the attack surface on perceptual or cognitive features [8] constitutes a formidable challenge for a tiered automotive industry that relies on deduction of requirements and verification of items through contractual quality management.

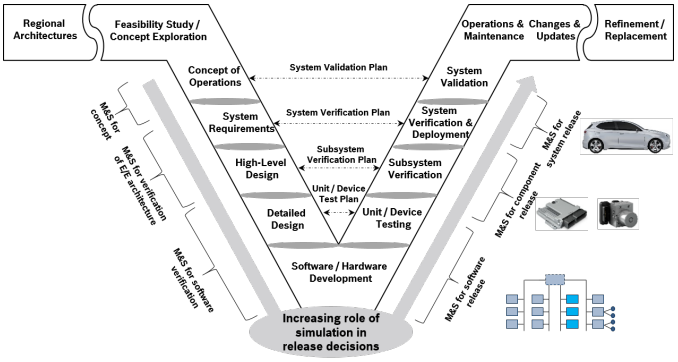


Fig. 1. Role of simulation in system engineering life-cycle

For non-functional properties the modelling problem [2] now enters through the backdoor: non-functional requirements, e.g. functional safety, depend on tight control of emergent properties (e.g. latency) that may have an impact on safety, reliability or, in the control theory sense, nominal performance. The problem can be partially managed by a careful architectural design that prevents non-functional insufficiencies (like single-point failure in redundant systems). System wide timing constraints, however, increase the interdependency of change processes in the tiered automotive industry, and many integration processes are required for any change. Maybe just for that reason, technologies that guarantee timing (e.g. OSEK time [9], TTP, FlexRay) aren't widely used or on the decline. Service oriented approaches, with Quality of Service (QoS), are trending but with a contractual approach (e.g. guaranteed latencies) the validation of contracts, and the verification of implementations, remain a complex topic, especially for ”hard” performance requirements. In this area where we propose a new verification and validation approach with SiL.

In general, SiL can support different test purposes in the development cycle of the automotive industry. Muresan and D. Pitica [10], for instance, presented a SiL environment with S-Function ECU interfaced to the DC motor control algorithm with measurement and verification of a virtual ECU using XCP. S. Schmidt et.al. [11] described the approach to maneuver- and event based testing of a vECU in a simulation environment with IPG CarMaker. An advantage of this approach is the reuse the maneuvers for ECU software validation by maintaining test consistent between HiL, SiL and Vehicle in the Loop (ViL) approaches. Linssen and F. Uphaus [12] demonstrated the validation of a full load acceleration maneuver of a vehicle in a SiL environment with multiple vECUs and plant models such as an engine model, a gearbox model, wheel models and a vehicle model. These use-cases, while being of great value for functional testing, typically do not address non-functional properties such as sensitivity to implementation time behavior.

In this paper, we discuss the drawbacks of hierarchical simulation environments with respect to the extended SOTIF life cycle (e.g. foreseeable updates during the useful life of a vehicle). Furthermore, the approach of hierarchical simulation environments imposes practical limitations to testing of cross-cutting concerns such as functional safety of distributed features. This work aims at proposing a novel separation of concerns approach which allows validation of contracts across functional and non-functional domains or organizational boundaries.

The paper is organized is follows: in Section II we describe the separation of test concerns with respect to simulation environment. Here, we also introduce the building blocks for SiL environments to effectively address these concerns. In Section III, we discuss how to ensure the credibility of the SiL environment to justify simulation-based release decisions. Further, in Section IV, the presented methods are demonstrated on a use-case combining functional simulation with time models. In the last Section V, we provide a summary of the results and a conclusion.

II. Software-in-the-Loop environments and components

Depending on the test objective, SiL environments can be classified as ”Feature SiL” ($\mathbb{F}$), ”Component SiL” ($\mathbb{C}$) and ”System Integration SiL” ($\mathbb{S}$). Fig. 2 represents these types in a Venn diagram. The intersections ($\mathbb{F}\cap\mathbb{C}$, $\mathbb{C}\cap\mathbb{S}$, $\mathbb{S}\cap\mathbb{F}$, $\mathbb{F}\cap\mathbb{C}\cap\mathbb{S}$) are particularly interesting: here contracts between vehicle level features and implementing technical components (ECUs) can be validated or even tested empirically (e.g. negative tests).

Functional software that is responsible for a feature [13] most often runs in a specific Electronic Control Unit (ECU) that is also the target of non-functional concerns in a divide-and-conquer fashion (”fail-safe feature” on the vehicle level). In ADAS or ADF systems, however, functional software is often distributed across multiple ECUs, at which point technical performance interferes with functional performance. That's even the case if novel so called ”vehicle computers” are used to co-locate services or virtual machines from different suppliers (the technical performance of the virtualization technology is a complex domain in its own). Furthermore, for function development it's useful to look at SiL use-cases with a varying degree of software allocation (e.g. architecture-as-a-model [14]). For clarity, we designate SiL use cases that look at the functional performance of ”not finally allocated” software with $\mathbb{F}$.

On the other side, the software as unit under test may include simulation models of ECUs, a method known as virtual ECU (vECU). These virtual ECUs can be co-simulated

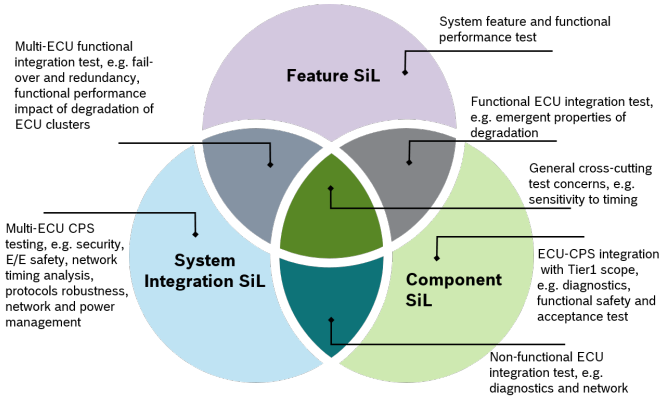


Fig. 2. Separation of concerns for SiL environments

with ”control plant” models (e.g. hydraulics valve models for ESP®) and environment models (e.g. road surface). We will use $\mathbb{C}$ to designate simulation environments that concentrate on ECU concerns and on the related software and system integration tests. They can be grouped in use-cases for SiL simulation, as provided in Table. I.

TABLE I
VECUS COMPATIBLE TO SIL DOMAINS

SiL Domains	vECU compatible
$\mathbb{F}$ (Feature SiL)	1, 2
$\mathbb{C}$ (Component SiL)	2, 3, 4
$\mathbb{S}$ (System Integration SiL)	2, 3
$\mathbb{F} \cap \mathbb{C}$	1, 2
$\mathbb{C} \cap \mathbb{S}$	2, 3, 4
$\mathbb{S} \cap \mathbb{F}$	2
$\mathbb{F} \cap \mathbb{C} \cap \mathbb{S}$	2

Finally, in a CPS, where functional software is distributed across multiple ECUs, depending on a system’s architectural design, the properties of networks and non-functional software (e.g. failure and degradation handling, latency, task prioritization) may determine functional performance. Additionally, non-functional requirements, like functional redundancy, applies at least to sections of the vehicle’s E/E system. For this, among others, emergent properties of network timing and Base Software (BSW), together with key aspects of the distributed feature, are the main test concern. The category of ”technical” system integration SiL systems is designated $\mathbb{S}$ in the lower-left part of Fig. 2.

TABLE II
TYPES OF VECU

Type	Composition
1	Single function (ASW/BSW module)
2	Multiple integrated functions (ASWs/BSW modules)
3	ASWs + RTE + BSWs and virtual hardware drivers
4	ASWs + RTE + BSWs and actual hardware drivers

Commercial products for ECU simulation, as given in Table-II [15], follow a top-down AUTOSAR approach from the OEM’s perspective that assumes a ”top-down” V-cycle, as proposed in Fig. 1. Unfortunately, little consideration is given to a bottom-up approach required by applied technology and its established test concerns. For an example, safety related diagnostics of tightly coupled mechatronic systems imposes constraints on the implementation of ECUs which can’t be modelled in AUTOSAR. In a top-down approach, this produces complexity and, in the worst case, ”white spots” in a positive test approach. The authors propose a compositional virtual ECU of Type-2 (refer to Fig. 3) that meets Tier-1 test concerns, e.g. BSW integration testing, enables new compositional verification methods, and helps to address the continuous life-cycle challenge imposed by SOTIF applications.

With the help of co-simulation, composition is also possible on the vehicle or environment level. Model containers like Functional Mockup Unit (FMU) [15] or Docker, enable a service oriented architecture for test and analysis, and IT architectures like Kubernetes enable test automation and scaling. Virtualized buses take the role of physical buses (e.g. automotive CAN) in a vehicle level system configuration. When addressing test concerns, the level of coupling between mechatronic and sensorics system must be chosen carefully as not to over-constrain the simulation. Typically functional vehicle level technical and component test concerns overlap at contractual interfaces (customer requirements) with acceptance test and system integration test. In the intersection $\mathbb{S} \cap \mathbb{C}$ (Fig. 2), compositional simulation environments can be used for cross cutting concerns, e.g. in multi-party integration testing. As an example, the use-case discussed in final section uses this method to combine simulation elements like functional SiL from domain $\mathbb{F}$, system level timing models from domain $\mathbb{S}$, and model parameters from the ECU domain $\mathbb{C}$ to uncover timing sensitivity as an emergent property of the system.

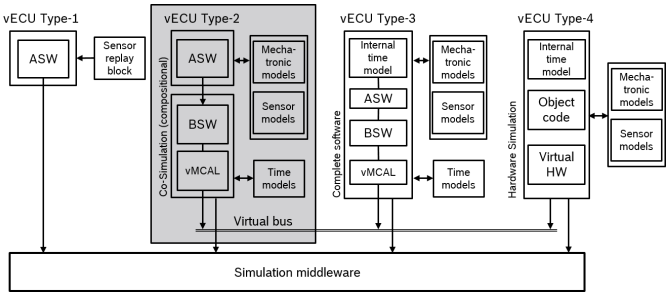


Fig. 3. Overview of vECU (virtual ECU) types

III. CREDIBILITY OF SIL ENVIRONMENT

Simulation will always lead to certain uncertainties of the simulation results, compared to the real behavior, which needs to be controlled. In the case of SOTIF, the validity of simulation results for certain concerns must even be ensured during the complete useful life of the end product [17].

Therefore, the result of the simulation must not only prove that the requirements of the software under test are fulfilled, but it must also be shown that errors introduced during

modeling or by the simulation environment are assessed and the simulation results are evaluated with regard to the quality of the simulation environment as such. Examples of such simulation artefacts are errors introduced by coupling, quantization or other numerical errors [10] [18] [19] resulting from the interaction between the components of SiL environment. Other errors are due to non-deterministic behavior of the tools connected to the SiL environment(e.g. measurement and calibration tools).

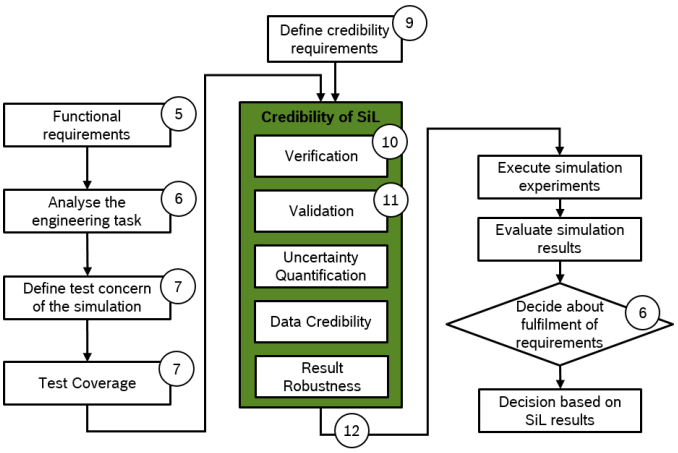


Fig. 4. Implementation and Qualification of SiL

The framework for assessing the credibility of simulation is well established [20]. However as discussed in the introduction, an important requirement of a SiL approach for SOTIF motivated lifecycle [3] is how well different cross-cutting concerns can be managed without gridlocks across organizational boundaries. In the way of resilient systems engineering we propose the following socio-technical approach:

- Establish an appropriate separation of concerns between domains that encourages falsification of requirements, assumptions and theories behind models.
- Define domain specific simulation environments that include models that are subjected to contracts with other organizational domains.
- Establish a test selection method that makes effective use overlapping simulation environments for relevant test concerns, including non-functional concerns, that enables verification of designs and the falsification of models.
- Establish and maintain a socio-technical system that ensures contract enforcement throughout the product lifecycle.

Fig. 4 illustrates the workflow to create and ensure the credibility of the SiL environment, adapting the approach in Figure 9 of ISO/PAS 21448:2019 standard document [3] and the circled numbers denote corresponding clauses within the same standard. The process starts with defining the functional requirements (*Clause 5: Functional and system specification*), followed by the analysis of the engineering task (*Clause 6: Identification and Evaluation of hazards caused by the intended functionality*), definition or separation of test concern of the simulation as discussed in Section II and test coverage (*Clause 7: Identification and Evaluation of triggering events*). Later assessing the credibility of SiL as per the established credibility methodologies [20] (*Clause 10: Verification of the SOTIF, Clause 11: Validation of the SOTIF*) and based on the credibility requirements (*Clause 9: Definition of the verification and validation strategy*). Finally evaluating the results (*Clause 12: Methodology and criteria for SOTIF release*) to make a software release decision based on the simulation results.

To ensure credibility in the software tested and released with SiL methodology, not only quality criteria have to be met but also methodological concerns need to be addressed [2] [4]: individual models used in SiL not only must have a sufficient level of detail and accuracy to meet test objective, but the architectural design of a SiL framework must also address cross-cutting concerns between different architectural scopes that depend on software. The epistemological problems (know-what) and deductive gaps between premises and conclusions always will create a credibility problem, unless a falsification approach is embraced [16].

The key takeaway is that models can be used as stand-ins for contracts (i.e. to test against the contracts) or they can be simulations that make emergent properties of systems visible (to check if the contracts are sufficiently complete). Both aspects, the deductive properties of models used in the domains $(\mathbb{F})$, $(\mathbb{C})$ and $(\mathbb{S})$, and the empirical and inductive simulation in the intersections ($\mathbb{F} \cap \mathbb{C}$, $\mathbb{C} \cap \mathbb{S}$, $\mathbb{S} \cap \mathbb{F}$, $\mathbb{F} \cap \mathbb{C} \cap \mathbb{S}$) contribute to provide empirical evidence for the correctness of the implementation and to validating the contracts. Additional methods for assuring the validity of models, e.g. field-based validation, may be required [2] [3].

IV. SiL environment for testing of ADF

The example in this section demonstrates separation of concerns methodology discussed in Section II, the block diagram of the SiL environment for this example (Fig. 5, for color mapping refer to Fig. 2) represents the $\mathbb{F} \cap \mathbb{C} \cap \mathbb{S}$ domain. Using this example, first we demonstrate functional simulation (*Process B*) of ADF modelled with fixed-sampling time in $\mathbb{F}$ domain. Second, the Worst Case Response Time (WCRT) is modelled in a time simulation framework (*Process A*) that uses parameters from HW performance measurements in $\mathbb{C} \cap \mathbb{S}$ domain. Finally, we present an example for a credible simulation in $\mathbb{F} \cap \mathbb{C}$ domain (*Process C*) to demonstrate emergent properties of nonfunctional performance that falsifies the initial modelling approach in $\mathbb{F}$ domain.

A. Description of the Processes

Process A: To create time models for demonstrating the emergent properties of nonfunctional performance in *Process C*, runtime measurements are performed using the methodology demonstrated in [21], parameters for the time models are obtained from the HW performance measurements. Later an analysis of the logical execution times (LET) is performed for the vECUs, which are used in the above mentioned SiL

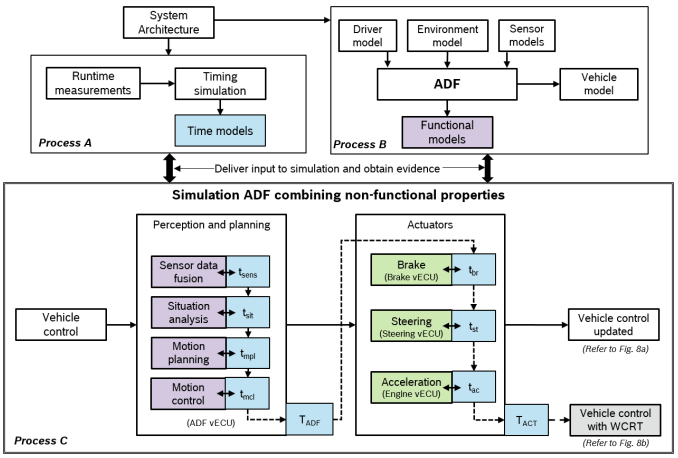


Fig. 5. SiL environment for testing ADF

environment for testing the ADF. Using this LET a Typical Worst Case Analysis (TWCA) of the ADF is performed according to the methodology illustrated in [22] and [23]. The Typical Worst Case Response Times (TWCRT) of the ADF and its relation to the actuator functions is shown in Fig. 6. These TWCRT are integrated to the vECUs in the SiL environment as time models (blue boxes in Fig. 5).

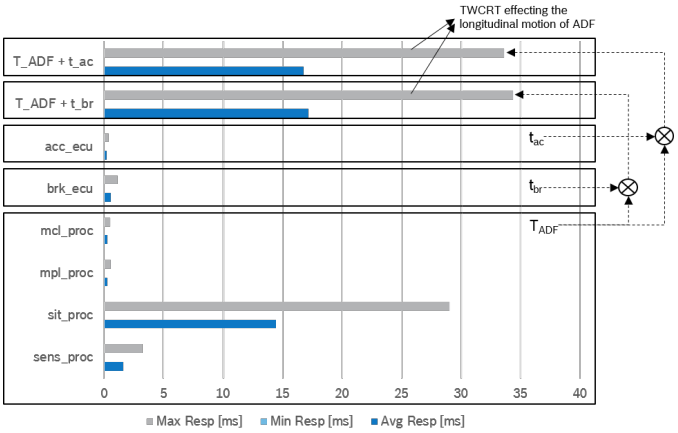


Fig. 6. Response times of functions in the SiL environment

Process B: For the functional verification of ADF with various test scenarios the SiL environment in domain $\mathbb{F}$ is implemented comprising of the functional models of driver, environment, vehicle, sensors and actuators interfaced to multiple vECUs governing the vehicle dynamics of the ADF. The ADF is distributed across several control units as per the system architecture and includes the functionalities for:

- Perception and planning comprising of the following functionalities as vECUs (of Type-2):
  - Sensor data fusion: to combine the data from the sensors such as radar, cameras, lidar, navigation, ultrasonic surround sensors as well as V2X.
  - Situation analysis: to interpret and predict of generic traffic situations as well as for the identification of driving strategies for ADF. This interpretation is based on the information provided by the perception of surrounding environment with different sensor combinations ranging from a single sensor (e.g. radar-only) up to complex multi sensor systems.
  - Motion planning: to provide the trajectory planning for lateral and longitudinal corridors also considering the driver comfort, to control the vehicle dynamics based on the perceived and predicted data of the road as well as surrounding environment.
  - Motion Control: to provide inputs to the actuators for lateral and longitudinal motion control.
- Actuation control: to control the lateral and longitudinal dynamics of the vehicle using the steering, acceleration and brake actuators. Separate vECU are employed for controlling the specific actuators (Type-3).

Process C: The time models from *Process A* are integrated with the functional models from *Process B* to create an effect chain for demonstrating the influence the TWCRT on the functional behavior of the ADF.

B. Results and discussion

In this example, functional testing is performed with a cut-in scenario as shown in Fig. 7. The test is considered to be successful in this scenario if the deceleration of the ego vehicle $-a_{x_{ego}}$ is within the comfort threshold limit $-a_{x_{limit}}$ (-2.0 m/s^2), the distance between the ego vehicle and new preceding vehicle is above a safe distance d_{safe} and no collision occurred between these two vehicles.

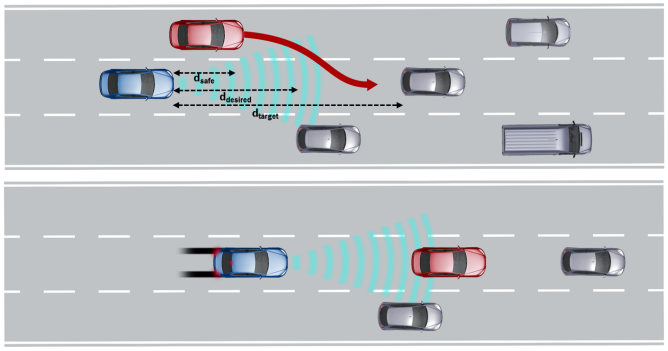
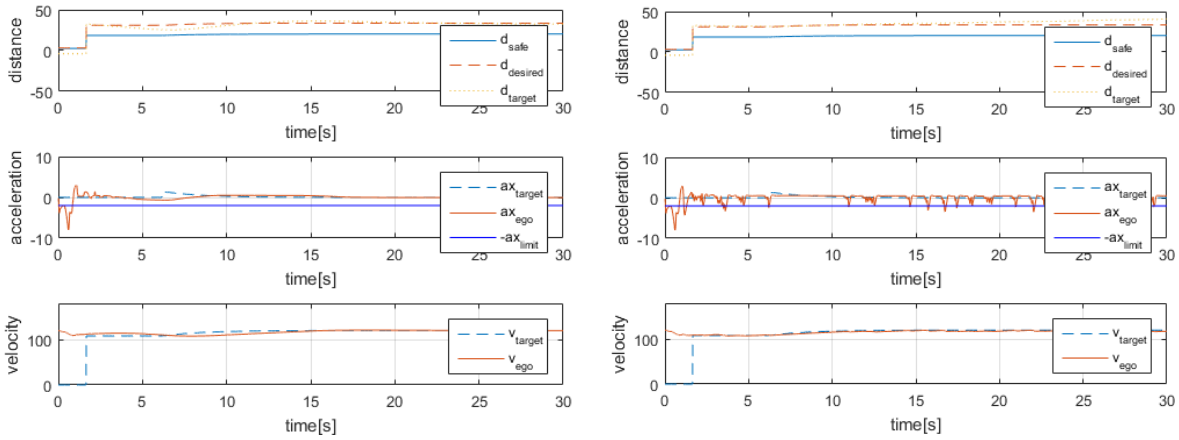


Fig. 7. Cut-in maneuver

As can be observed from the results of the functional simulation without TWCRT as shown in the Fig. 8a, the deceleration $-a_{x_{ego}}$ of the vehicle is smooth and well within the comfort deceleration threshold. Also the distance between the ego vehicle and the new preceding vehicle is maintained above the safe distance d_{safe} and also the desired distance $d_{desired}$.

When the TWCRT is integrated as time models in the SiL environment and simulated in closed loop, the deceleration of the ego vehicle $-a_{x_{ego}}$ is frequently above the comfort threshold limit of $-a_{x_{limit}}$ as shown in the Fig. 8b. This is due to the fact that worst case response time (T_{ADF}) in the



a. Cut-in maneuver function response

b. Cut-in maneuver with TWCRT

Fig. 8. Results of functional and non-functional response of ADF in SiL environment

ADF vECU propagates to impact the (T_{ACT}) of the brake and accelerator actuation, effecting the entire longitudinal control strategy.

The simulation result not only falsifies the initially used fixed-sampling time modeling approach, it also allows to derive requirements for latency that can be used as contracts for deployment of SW function to ECUs. This example also shows that simulation environments in the intersection of Feature, System and Component SiL domains, can be efficiently used for the validation of contracts, e.g. for non-functional properties.

V. Conclusion and Remarks

In this paper we discussed a novel method for structuring test concerns using different types of SiL and nonfunctional simulations, a new type of composable vECU is presented that enables building SiL systems for wide array of test concerns throughout the extended lifecycle, that is required by emerging open context applications. We also discussed how SiL simulation credibility can be established across organizational boundaries and demonstrated that simulation environments in the intersection of Feature, System and Component SiL domains can be efficiently used for the validation of contracts.

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