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# Evaluating autonomous functions performance through simulation using interoperable sensor, vehicle, and environment models

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**Abstract**—In this paper we present the simulation software tool Pro-SiVIC for verifying and validating of Advanced Driver Assistance Systems (ADAS) and autonomous (self-driving) vehicles. The specificity of Pro-SiVIC lies in the in-depth virtual prototyping of new or improved perception sensors, and in simulating numerous indoor/outdoor scenarios combining vehicles, obstacles, climate conditions, environment and sensors. Such simulations enable virtual verification and validation of perception algorithms and sensor settings. Pro-SiVIC has been designed to help engineers to build realistic real-life 3D scenarios and experience parts of autonomous functions virtually. As a result, the need for physical prototypes is reduced and in some cases even eliminated at different development stages from early design to final validation. We will show how the software sensor models can simulate environmental factors that influence sensor performance such as lighting conditions, weather, and characteristics and behavior of other road users. We will also illustrate how the platform can be connected to real-time data management, to the other tools which use different algorithms of perception, post-processing, data-fusion, path planning and control. The process can be applied so users can quickly and precisely study the performance of embedded systems in both typical and critical use cases, to ensure the product will be safe and reliable in operation.

**Index Terms**—ADAS, Autonomous vehicles, sensors, LIDAR, RADAR, camera, Ultrasonic, GPS, NCAP, NHTSA, post-processing, tracking, data fusion, interoperability, Open Scenario & Open Drive.

## I. MOTIVATION

Ensuring the reliability of the perception of an intelligent vehicle is recognized as one of the challenges for the transition to the higher levels of autonomous driving [1], [2]. From a technological perspective, safety is enforced using combinations of sensors systems exploiting different physics principles used by optical sensor such as camera [3], fisheye [5], and cyclops device, by near infrared sensors like laser scanner [6], [7], thermal IR sensor [10], ultrasonic sensors [11], electromagnetic sensors like RADAR and radiofrequency [8], [9]. Each sensing system is defined by its own hardware components, electronics and detection function with embedded processing which deliver a variable performance according to the driving environment characteristics [12].

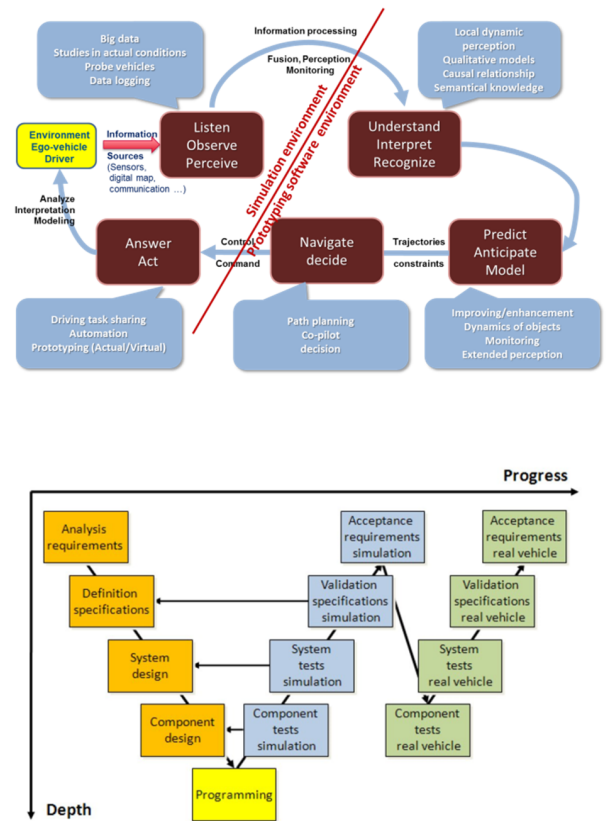


Fig. 1: Information processing and propagation for CAV, a complex multiple layers system with microscopic and technological levels

Validating of perception functions for autonomous driving and of the sub-functions involving the detection, tracking [15], object recognition [16] (fig 1) is extremely complex by the extent and the variety of the conditions to be tested (sensor, infrastructure, object, weather, features) [17], [18]. Gradually, the industry has embraced the idea of introducing simulation

methods to support such validation [4], [25], [26]. According to the perimeter of each sub-system to validate and to the level of representativeness of the simulations, the way to simulate sensing systems can be different [23]. Ranging from fully idealized sensing function to detailed physics simulation of the sensor, such models deliver different value in the evaluation process by comparison to real testing [22], [30]. Yet with the growing ambition producing high-fidelity virtual prototypes of autonomous vehicles, the physics-based simulation sensor is becoming a necessity to address the in-operation system performance [24], [31], [32]. To fit in actual development processes, such simulation must also be interoperable with other vehicle components and system simulation, which is a driving force for the emerging standards for co-simulation management, model exchange, and data exchange [27]–[29]. Now, the design processes is not only a V cycle but a W cycle with a first part in simulation (figure 1).

In the new generations of simulation platform, the problem is to address a complex multi-layers issue not only processed by one software and one computer but by several interoperable remote platforms (i.e Dynamics vehicle modeling, sensors modeling, communication modeling, and traffic modeling). Such a simulation platform must respect a couple of important constraints such as interconnection with real-time data management and processing software, or the capability to share the simulation components, the processing stages, and the applications running on several applications and/or computers.

## II. THE INTERESTS OF AUTONOMOUS VEHICLE AND ADAS SIMULATION

The design and development process of the new generation of C-ITS (Connected Intelligent Transportation System) and ADAS (Advanced Driver-Assistance Systems) for autonomous driving functions lift to majors challenges. Testing process needs driving several million kilometers is necessary to validate a system in many types of urban and traffic environments. These tests must be performed day and night under different weather conditions (fog, rain, snow, dust, etc). Ensuring that all required conditions are statistically met during the test phases is not trivial. On the other hand, track tests are usually controlled where trajectories, speeds and traffic density are defined in advance. These tests therefore represent only part of the scenarios and real situations that can be encountered in real traffic world.

Simulation can give complex systems performance from well-defined scenarios and configurations. It intervenes in several phases of system manufacturing in particular the design and exploitation phases. With virtual prototyping, simulation can be used to predict in real time the system behavior with respect to its control in order to implement optimal strategies. It is also used for verification, validation and improvement of choices in the design phase. The evolution in last years of ADAS towards higher level of automation has brought in its wake the usage and the emergence of a multitude of simulation platforms and models. Simulation has gained traction due to the complexity of the systems involved, the amount of testing

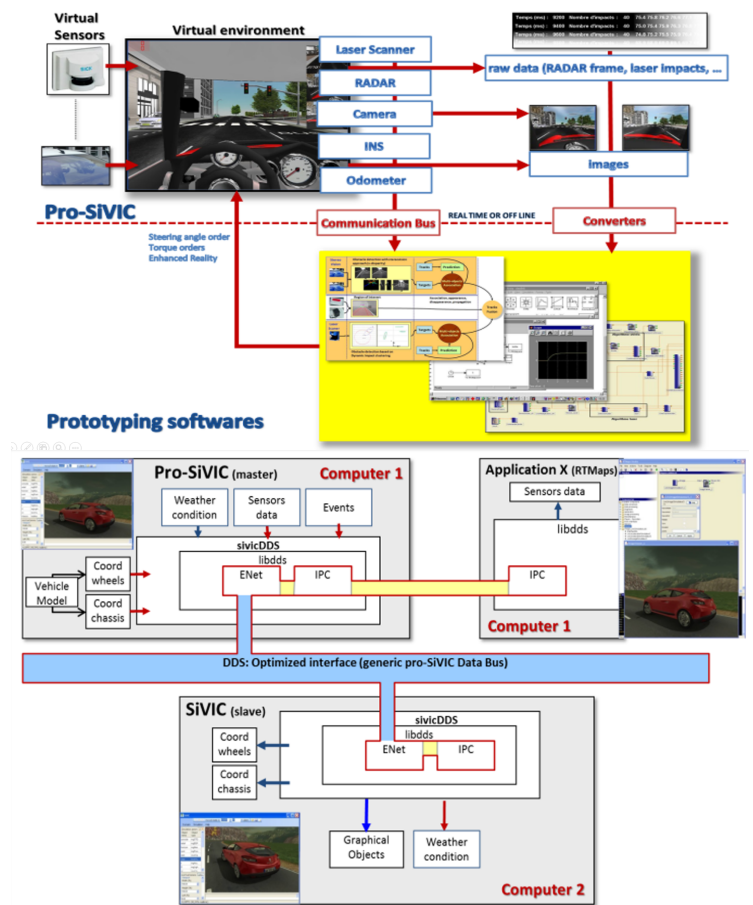


Fig. 2: Interoperable simulation architectures for distributed HIL and SIL application prototyping, testing, and evaluation

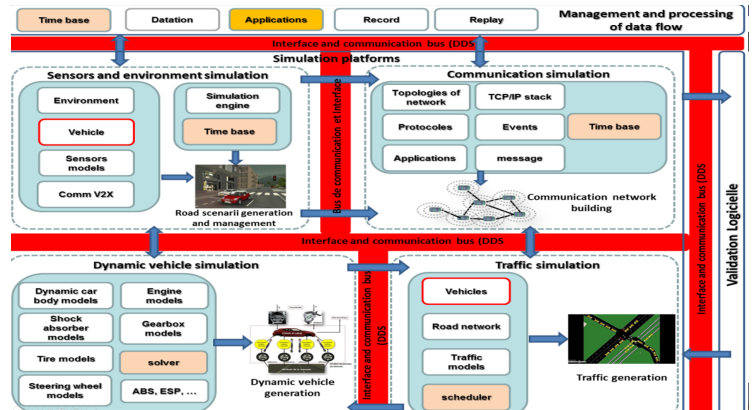


Fig. 3: Simulation platform involving dedicated simulation modules (Sensors, vehicles dynamics, environment, communication, traffic, processing)

required to cover their operational design domain and the new safety issues to address. However, simulators are distinguished by their different application domains, solvers and calculation methods (figure 3) [2]. The testing through simulation of a complex system therefore requires several simulation tools,

with each covering its domain. There seems to be an agreement among car manufacturers, that since no current simulation tool fits all needs for the tests and a lot of flexibility is required, the self-performance and interoperability of simulation tools will be key. As an example, for the design of a SAE level 3 function using multiple sensors, virtual driving needs a platform to simulate the sensor behavior with required accuracy, vehicle dynamics, vehicles environment, virtual road and infrastructure information. Indeed, not only the traffic situation influences the decisions made by the ADAS, but the simulation of the performance of the sensing is determining in the ability to capture this situation correctly. In addition, it has been shown in [17], [18] that the vehicle dynamic influences the data received by the sensors which can induce false detections or misinterpretation of the environment. On the other hand, the raw data from the simulation of the various sensors are used to extract information or injected into process/fusion algorithms or simulation platforms [1]. Comprehensive modeling of the complex system and efficient simulation of all parameters can only be achieved through the exploitation of interoperability methodological approaches. However, the state of the art in automotive and ADAS area is still lacking standardization of the applied solutions.

### III. PRO-SiVIC FOR HIGHLY AUTONOMOUS COOPERATIVE DRIVING SYSTEMS IN EVERYDAY TRAFFIC

Study and improving a complex system in order to obtain high level of passenger safety and autonomous driving requires also to have data besides the perception of the environment by the Ego-vehicle. As an example, if we look at to the connected cars, their wireless connections will allow them to offer automated driving processes and to exchange traffic data. However, it remains to define the communication protocols. V2V technology is dedicated to inter-vehicle communication at short-range distances, which offers the advantage of its immediate availability for the integration of connected security functions. The use of the 5G network will allow vehicles to share environmental information and communication with surrounding infrastructure and pedestrians, thereby reducing road risks and accidents.

The major information that can be transmitted is the road traffic density. This later is related to different parameters like cars numbers speed, road size, etc. As regards road traffic, simulators based on probabilistic methods for generating traffic have been developed. These solutions simulate the behavior of the vehicle based on macro and micro traffic characteristics but in most cases these types of simulator assume that the vehicle is a point of the road without any dynamics [19], [20] [21]. In addition to these complexities, the computer power, memory space and data communication requirements for real-time simulation of these complex scenarios will need dedicated and special hardware/software architectures. We realize that for such situations, the ego vehicle perception is no longer enough and that it is essential to have a simulation environment that allows prototyping and evaluation of systems extensive, enriched and cooperative driving assistance. To solve these



Fig. 4: Example of Pro-SiVIC environment where the ego-vehicle is equipped by multiple sensors.



Fig. 5: Example of Pro-SiVIC weather conditions simulation (rain drops, inhomogeneous fog, and wet road surface).

constraints, the Pro-SiVIC solution offers a wide choice of real time simulation. Pro-SiVIC is a virtual prototyping platform, which allows to carry out physically realistic 3D simulations of environments and sensors, like those used in Advanced Driver Assistance Systems (ADAS), including infrastructures, road users, vehicle dynamics and multi-technology perception sensors, in a completely virtual environment (see Figure 4). It also allows sensor perturbation by harsh weather condition like fog, rain, snow and luminance (see figure 5 and figure 6).

Pro-SiVIC is coupled with other tools which use different algorithms of perception, post-processing, data-fusion, path planning and control. The generated flow data are time-stamped and synchronized. These data can be recorded by data acquisition systems such as Intemporas RTMaps, ROS, Scilab (see figure 2). The Pro-SiVIC architecture also allows an easy integration of a complex mathematical dynamic model that we design primarily on Matlab-Simulink, Scilab-Xcos or Simulation-X, for real-time integration with external equipments (SIL: Software In the Loop and HIL: Hardware In the Loop) forming closed-loop systems [12], [13] [14]. This gives the possibility to easily share data between several development teams. Engineers can perform safety studies



Fig. 6: Example of Pro-SiVIC light conditions simulation.

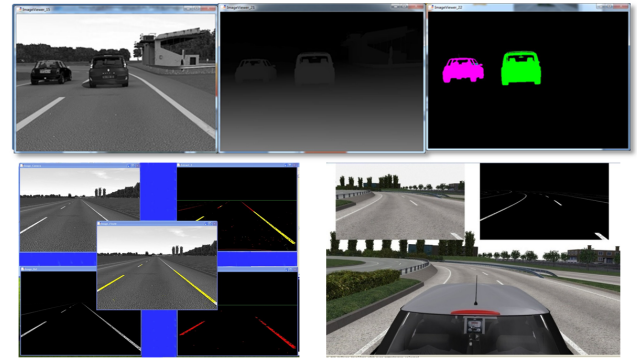


Fig. 9: The generation of the ground truth for an efficient and accurate evaluation stage

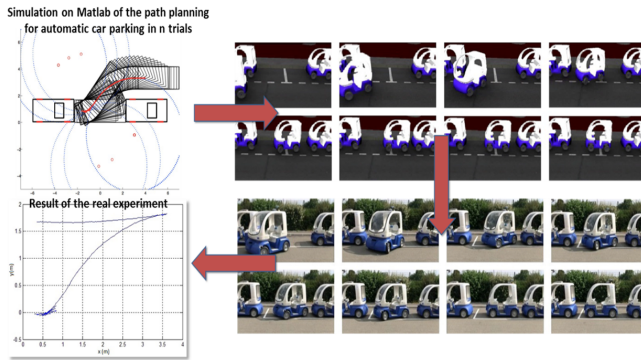


Fig. 7: From virtual to real prototyping: application to the automated park maneuver.

on the integration of the algorithms and control functions before implementation. They can analyze system performance and sensor robustness, visualize scenarios involving vehicles, humans, objects and surrounding environment. Any scenario can be replayed in order to compare sensors side-by-side as well as assess fault diagnosis and system reconfiguration to achieve degraded, or limp-home functionality. Pro-SiVIC can be then used totally as software in the closed and open loop or partially hardware in the loop for autonomous vehicles, ADAS, design and validation [25].

About the evaluation and validation stages, Pro-SiVIC also offer functionalities allowing to easily and automatically generate a set of ground truth. This functionality is mainly due to the implementation of an efficient layer mechanism.



Fig. 8: From virtual to real prototyping: application to the autonomous driving.

#### IV. CONNECTION BETWEEN SIMULATION PLATFORMS

The reproduction of a physical phenomenon or an engineering system by simulation is based on mathematical modeling. Mathematical models are among the tools widely used by scientists and engineers to understand, diagnose and predict phenomena. However, the models must interoperate to realize all the simulation of the system. Indeed, the data issued from different models has no utility if we did not have algorithms to interpret and extract useful information. Therefore, it is essential to define the interoperability of the models in order to exchange data between different simulators and algorithms. Interoperability can be defined as the ability of two or more simulators to communicate and cooperate despite differences in the implementation language, the execution environment, or the model abstraction. This interoperability can be based on more standardization of models and or by computer engineering methods. An example of connection between simulators consist on the exchange of the data files. The simulator A executes its algorithm record data into file. This file is then imported to the simulator B. This method is used in many cases. However, in a complex system where several simulators are needed to run, the sharing files becomes complicated and needs make sure on the files compatibility.

One of the methods called co-modeling is based on a unique language. Engineers and scientific can therefore choose a programming language such as Fortran, C ++, Java, Python, etc. This approach has advantages, but each domain has its own particularities in simulation. Imposing a unique programming language can quickly become binding. Moreover, this method makes it possible to have access to the mathematical models which are not authorized by the software suppliers.

Another common method is co-simulation in which each simulator is model or smaller systems, which can operate independently of each other. Each simulator processes a part of the complex system and exchanges data at discrete communication points. However, co-simulation requires some standard for connecting simulators and exchanging data. As an example, the FMI (Functional Mock-up Interface) is a standard that support model exchange and co-simulation of simulators using a

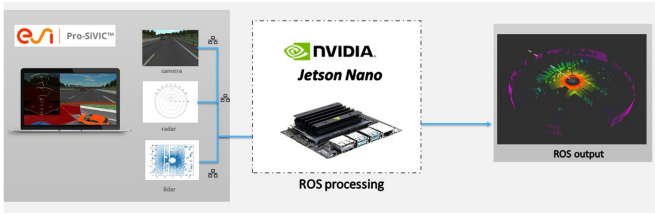


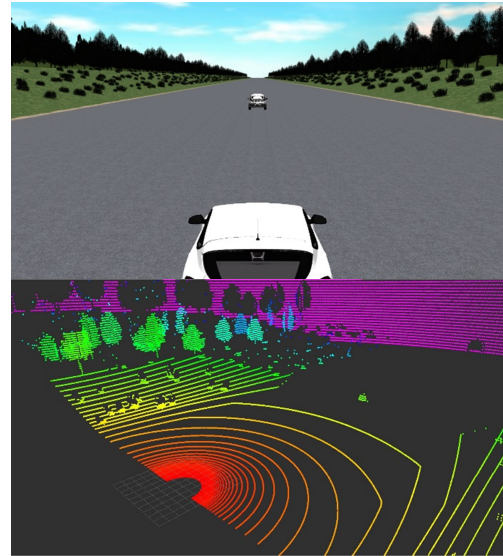
Fig. 10: The generation of the ground truth for an efficient and accurate evaluation stage

xml-files and compiled C-code. The Data Distribution Service (DDS) standard is a technology for distributing high volumes of data, dependably and with predictable low latencies. This technology is used in different area and is recommended and mandated as the technology for real-time data distribution by several key administrations. Thanks to the Interoperability, experts can work on its part of the problem with its own tools without having the coupled system in mind and eases the relationship between system integrators and suppliers [see figures 2 and 3].

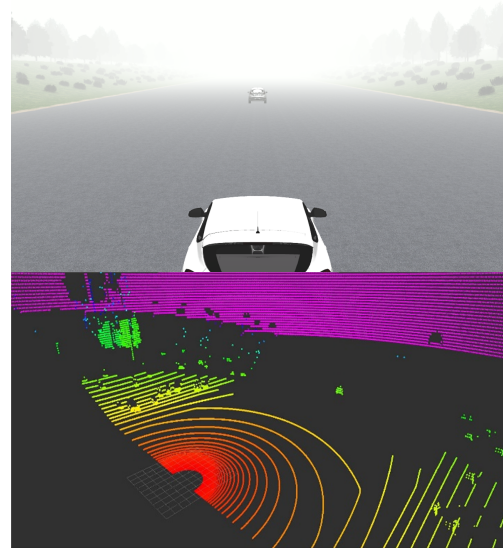
#### V. EXAMPLE OF PRO-SiVIC INTEROPERABILITY

To evaluate the performance of algorithms for processing and decision making in autonomous multi-vehicular scenarios, we need to use a set of simulation tools that can operate in real time and emulate real conditions as closely as possible. In this demonstration we use Pro-SiVIC to simulate an automotive LIDAR disturbed by weather condition and ROS software to show LASER data. The Pro-SiVIC software is running on simple laptop while the ROS software is running in a NVIDIA Jetson Nano (see figure 10). The Data Distributed Storage (DDS) bus is used to transmit environment simulation information about vehicles mobility and signal propagation to the network simulator, and sensor data to the data management framework. In this demonstration simulators are synchronized to the Pro-SiVIC time and the LIDAR sensor is placed on the front bumper of ego vehicle which evolves in a track environment.

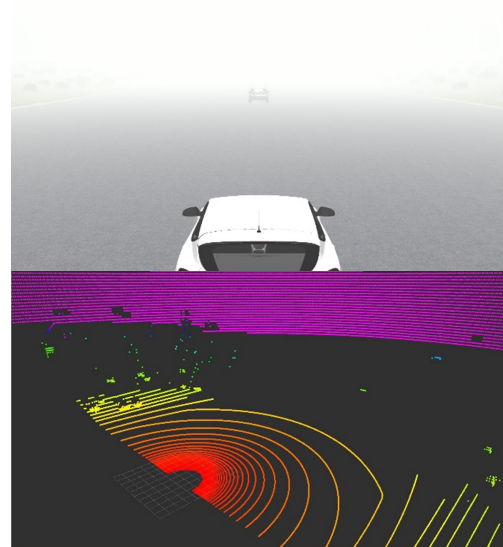
As advanced as the LIDAR may be, no current single sensor system guarantees a perfect accuracy of the measurement. The performance of LIDARs decreases in adverse weather conditions like rain or snow or when the sensor gets blocked by e.g. dirt. The scenario illustrated in figure 11 represents the car to car Automated Emergency Breaking NCAP test in clear weather (figure 11a), medium and strong fog density (figures 11b and 11c respectively). The LIDAR data are represented by a 3D points cloud in ROS where LASER impacts with objects are represented with a gradient color as a function of distance and reflectivity. Regarding to the pink dots, these represents the LASER non-impacts whose are projected at the maximum range of lidar and it is equal to 120 m in this simulation. When comparing with clear weather which is considered as a best case of sensor operation (figure 11a), we can see that the LIDAR images (raw data) deteriorate as the fog density increases (figures 11b and 11c). This degradation in LIDAR



(a) clear weather



(b) Medium fog density



(c) Strong fog density

Fig. 11: Simulation of the LIDAR sensor in Pro-SiVIC and representation of the laser points cloud in ROS. Simulation are performed in clear weather medium and strong fog strong fog density.

images is related to attenuation of laser energy by fog particles. Indeed, the moist air acts as a screen for the infrared radiation where fog particles reduce laser intensity by absorption and diffusion phenomena. These simulations shows that harsh weather condition may cause LIDAR system outage due to the attenuation signal attenuation.

The Pro-SiVIC helps to simulate all NCAP test in extreme situation and different weather conditions with an independent sensor manufacturer software. In addition, Pro-SiVIC can be applied for detecting different object (cars, pedestrians, animal, road signs, .), road marking. The method used to test LIDAR performance under harsh weather condition and perturbation can be used as a method to compare different sensors issued from different manufacturers. Assigning a score to the different sensors based on the number of detections will this allow to classify sensors according to their performances.

## VI. CONCLUSION

In this article, we have presented the simulation platform Pro-SiVIC that is dedicated to the simulation of autonomous and connected vehicles and ADAS systems. This simulation tool is used to test systems using Optical, Electromagnetic and Acoustic sensors for perception in intelligent driving systems. It also allows a realistic simulation of the sensors with the influence of the vehicle dynamics and the disturbance from degraded weather conditions. Its architecture allows to connect to other simulation platform to facilitate communication and interoperability. The reliability and robustness of the perception, data fusion, co-pilot and control algorithms can then be improved and measured virtually. With real-time testing in extreme conditions, innovative advanced driver assistance systems can be explored in depth without the need for costly and complex tools such as instrumented cars and infrastructure. According to the target performance needs for the function, the required level of sensor simulation (physics based or reference) can be adapted. In this way, simulation can be used with more flexibility and applications can be developed without always resorting to complex environment modeling. Nevertheless, simulation may not yet be regarded self-sufficient in an entire development process. After prototyping a function virtually and measuring its performance, the complete solution would then be embedded on-vehicle for real testing. Since the performance of the function was already tested virtually in realistic conditions, the real tests may begin with much higher confidence on the function performance than without this virtual prototyping stage. The confidence gained from simulation can reduce the risk of testing and development cycles to achieve the expected performance. This simulation platform represents a real benefit for upfront design and offers a valuable support to the development of cooperative systems such as V2V and V2X [2], [31] and the assessment of their performance and reliability.

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