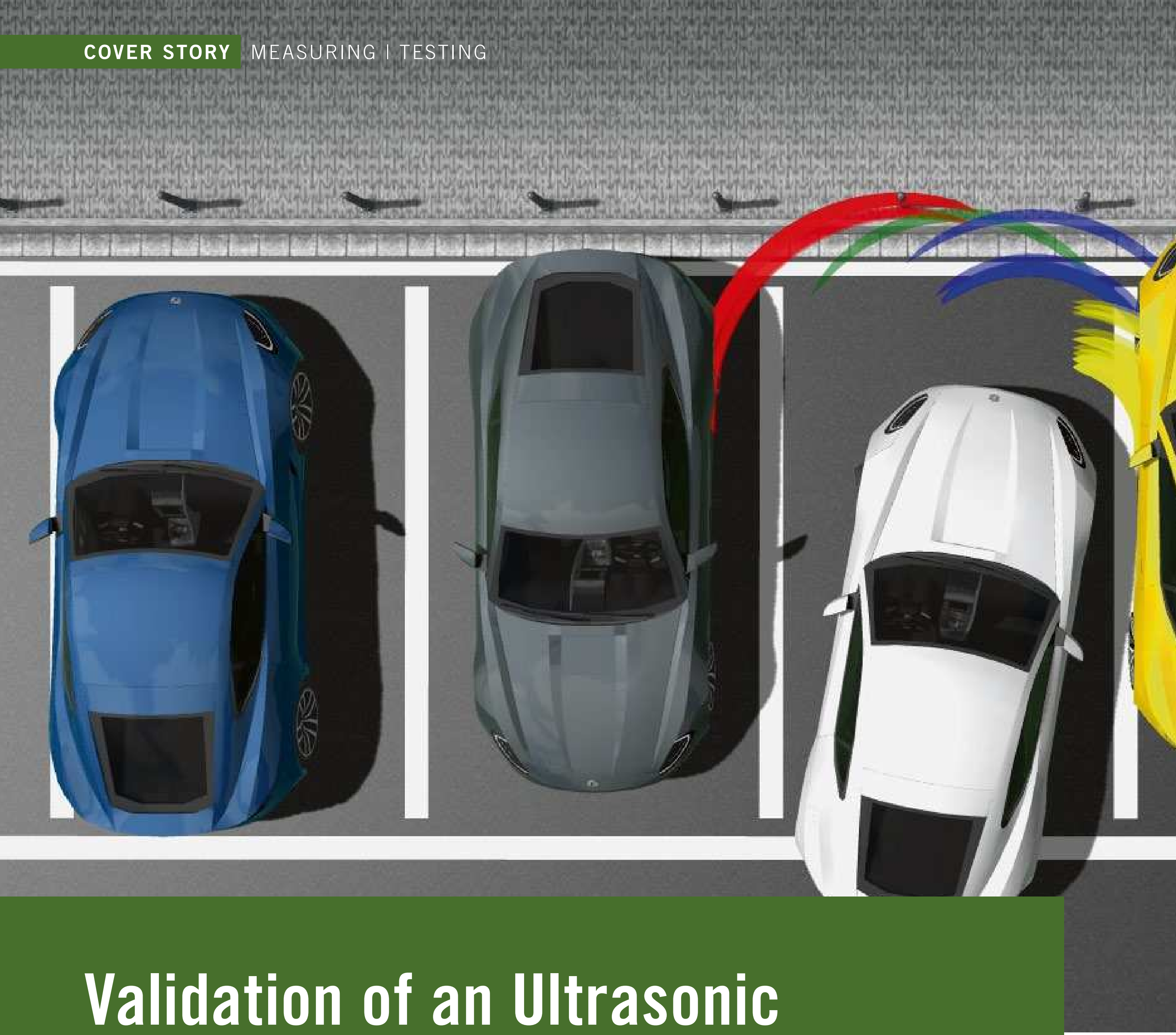

Validation of an Ultrasonic Sensor Model for Application in a Simulation Platform

IPG Automotive and Continental Autonomous Mobility Germany report on a validation project they carried out jointly. The project's objective was to validate the ultrasonic sensor model in the simulation environment CarMaker using a real-world ultrasonic sensor from Continental. The aim was to demonstrate that a realistic simulation of according sensors considering all relevant effects of the signal chain is possible.

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Ultrasonic sensors are well established in automotive manufacturing. In the entry-level segment, they are used as simple, purely ultrasonic-based park assist but also for automated parking systems. Their capabilities however go much further than the familiar applications. To enable the increasing automation degree of SAE level 4 and 5 vehicles, they are also highly relevant for autonomous parking functions for example. This holds true for the isolated use of ultrasonic sensors as well as use in combination with other sensors within the scope of sensor data fusion. Additionally, a system transfer to larger vehicle classes such as trucks increases the number of sensors and thus the complexity of the entire system.

To address this challenge, the automotive industry now consistently uses simulation solutions, which can model the environment as well as the vehicle's sensor technology and, in this way, replace real-world test drives in many cases. One advantage of simulation is for example the detection of weaknesses in sensor packaging at a very early design stage, which can result in reduced costs. Furthermore, it enables identifying critical test cases through the generation of synthetic raw sensor data that can be analyzed downstream in the event chain. Simulation also offers the option to generate realistic, reproducible echoes that serve realistic signal processing and are thus interesting for parameter optimization as well.

DEVELOPING SENSOR APPLICATIONS WITH SIMULATION

The validation project described hereafter used the open integration and test platform CarMaker, which enables sensor simulation of a full SAE level 4+ vehicle by means of different architectural components. It provides physical sensor models for various sensor technologies such as radar, camera, ultrasonic and lidar. This article focuses on

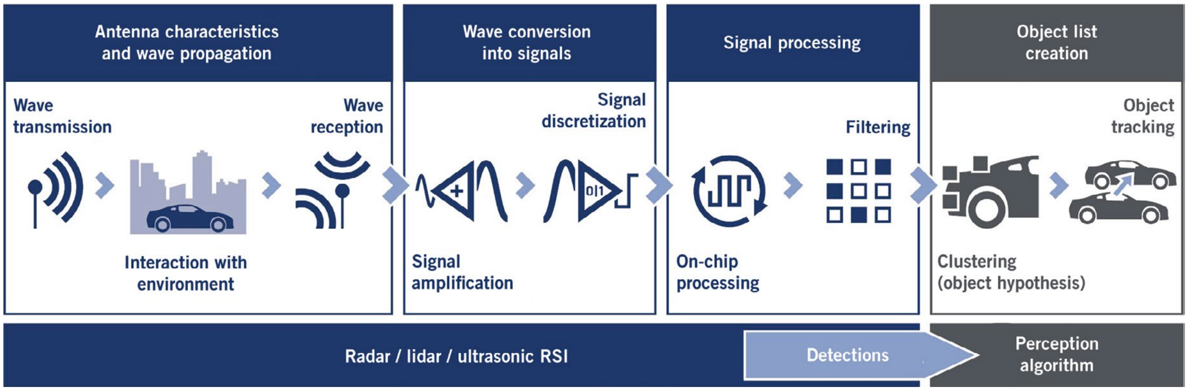

FIGURE 1 Signal chain of the RSI sensor models (© IPG Automotive)

the real-time capable ultrasonic sensor model Ultrasonic RSI, a model based on ray tracing.

It enables access to the sensor's physical raw data, from which the term Raw Signal Interface, in short RSI, was deduced. The model is based on the signal chain of a real ultrasonic sensor and complemented by the generation of an object list from the detections emitted by the sensor. Generating the object list is the user's task. **FIGURE 1** exemplifies this signal chain that is also modeled by the Ultrasonic RSI sensor model. It starts with the illumination of the environment by a transmitter, which emits sound waves into the environment. In this process, the sound waves are discretized into a finite number of rays. This allows balancing simulation speed and physical accuracy. Considering environmental conditions that have physical effects on the wave propagation, the Helmholtz equation is applied to calculate electrical scatter fields on object surfaces using parameterizable material properties from which reflections are determined. Following this, all relevant rays go back to the receiver. **FIGURE 2** illustrates the ray tracing algorithm to simulate a sound wave.

The sound pressure level as well as the time of flight of the ray are output for all detections of the sensor model. The dense packaging as well as the concomitant effects are taken into account by an optional detection of cross echoes of sensors among themselves. Interfaces between the boxes of the signal chain allow replacing individual steps with user-defined code. Clustering on available GPUs optimizes performance while fully exploiting resources. The associated hardware supports high-performance ray tracing as well as the injection of sensor data into the control unit to realize a closed-loop simulation. In addition to the described RSI sensors, among which the ultrasonic sensor model ranks, CarMaker offers further sensor categories. These sensors can bypass the chain and directly provide object lists based on ground truth data to users.

VALIDATION AND METHODOLOGY

The goal of the joint validation project was to explain that, with suitable parameterization, the Ultrasonic RSI is capable of realistically simulating a real sensor. Moreover, the project aimed at obtaining a validated model emulating all relevant effects of the signal chain. Both project partners were able to benefit from the validation project. As a developer for ultrasonic sensor components including processing technology and algorithms, Continental benefited from the open integration and test platform CarMaker that transforms high-resolution environments with detailed ultrasonic sensor models into synthetic raw signals. IPG Automotive in turn was able to utilize the means of a sensor manu-

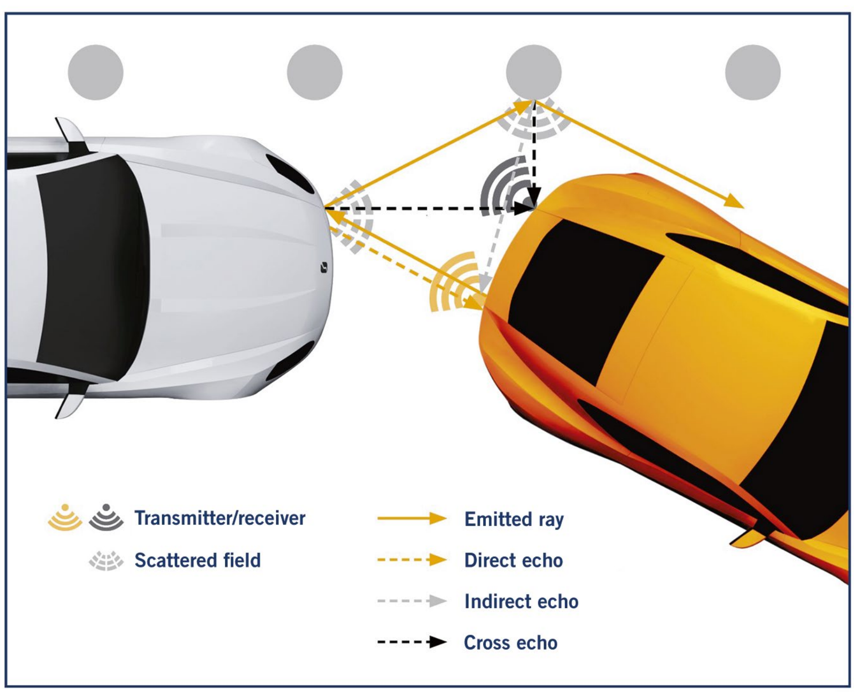

FIGURE 2 Schematic representation of the ray tracing algorithm to simulate a sound wave (© IPG Automotive)

facturer to verify own sensor models and to validate the correlation of synthetic and real data.

In line with expectations, the validation process showed that every modeling has systemic boundaries. A sound sensitivity analysis was thus essential. It analyzed which parameters had the most substantial impact on sensor output in terms of for example amplitude, noise and separability (parameter to classify the separability of two objects at similar or identical distances). Against this backdrop, examining scenarios, test objects and test setups that result in sound and reproducible assertions for model validation was required. This is why a detailed test catalog was developed in close collaboration to successfully implement the joint validation project. This test catalog ensured sufficient test coverage to validate typical effects from ultrasonic sensors. Based on the measurement results, the current generation of the Ultrasonic RSI sensor model was developed further. **FIGURE 3** depicts two complex test setups. In test A, two tubes were placed in front of the sensor at the same distance to examine the separability of two identical objects. Afterwards, the distance of one of the tubes to the sensor was reduced and increased once respectively. In test B, a plate was mounted at a fixed distance to the sensor and then rotated to detect and analyze wave-typical interference patterns.

Ultrasonic-based systems typically generate at least two raw data streams per measurement in addition to secondary information. On the one hand, in general, one describes the distance to an object that is calculated using the time of flight; so, the time that passes until the wave emitted by the sensor is received again. On the other hand, the other describes the amplitude with which characteristics of a reflection point can be determined for example. In this context, a measurement is classified either as burst or as reception. A burst designates the emission of an ultrasonic wave, whereas the reception designates the reception of a reflection. Depending on the system, these streams can contain further information such as double rates or additional timing information. Typical effects are primary and secondary, or direct and indirect reflections of objects which are caused by ground reflections for example. In addition to determining basic sen-

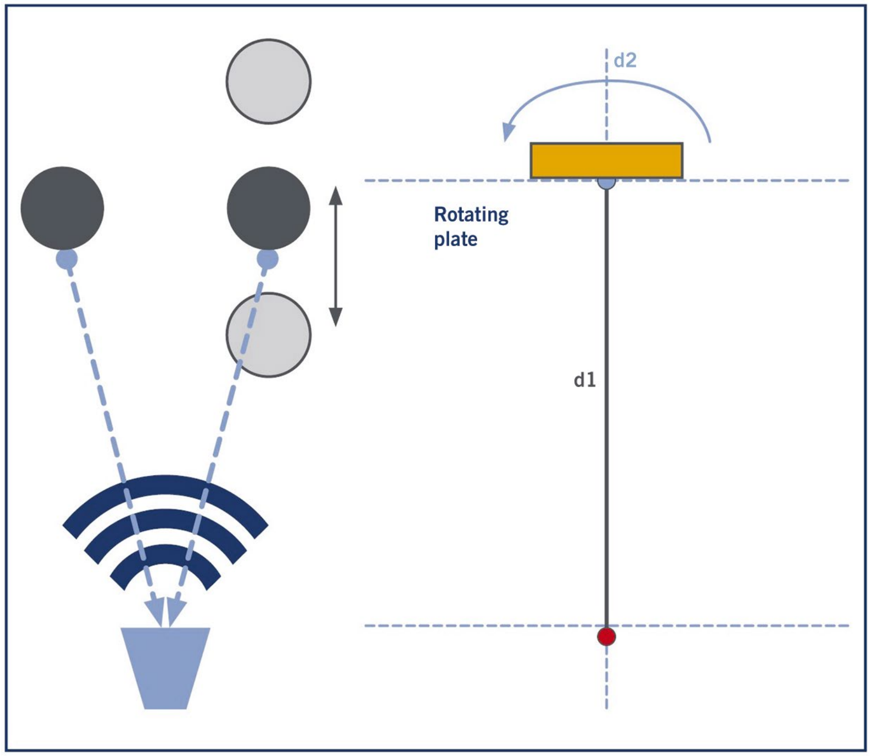

FIGURE 3 Test setup A (left) and B (right) to validate the sensor model Ultrasonic RSI (© Continental | IPG Automotive)

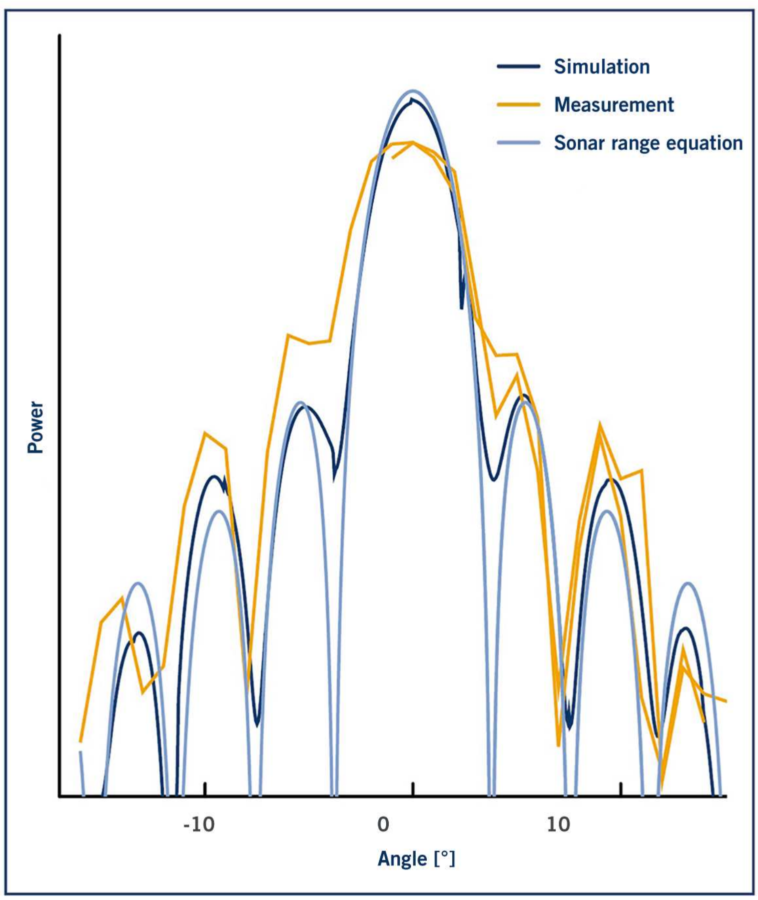

FIGURE 4 Results of the test “turnable plate” and comparison with the data calculated in simulation (schematically) (© Continental | IPG Automotive)

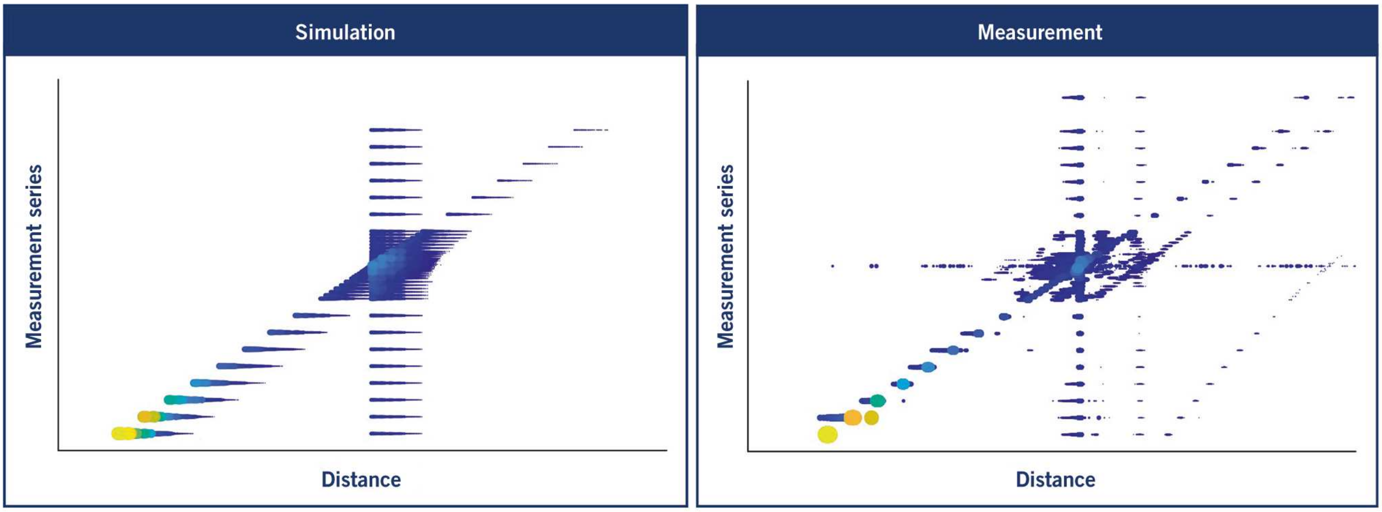

FIGURE 5 Results of the separability measurement in simulation and real measurement (schematically) (© Continental | IPG Automotive)

sor properties for transfer to the sensor model, such as range, field of view (FoV) and noise behavior, the separability between two objects and the precision of measurement were examined. Intensive sensor testing allowed for specification of these and further characteristics such as radiating characteristics in azimuth and elevation and replication in the virtual environment.

The measurements within the project were all performed on test benches of Continental Autonomous Mobility Germany. The used measurement technology as well as the signal processing chain represented exact copies of the system components that are put to use in the real-world vehicle as well.

RESULTS AND ANALYSIS

FIGURE 4 illustrates the results of the test 'turnable plate' and shows a comparison with the data calculated in simulation. This experiment was performed to indicate how well wave-typical interference patterns can be reproduced in simulation (**FIGURE 3**, test B). The measured power at the receiver between simulation and measurement compared in good approximation and also coincided with the physical theory of sonar range equation. The congruence of the local minima and maxima was also clearly recognizable. Particularly with a very small plate edge length of 5 cm, this provided information about the quality and resolution of the simulation. This type of investigation allows for precise determination of parameters of the ray tracing sensor in order to achieve realistic results even in complex driving scenarios.

FIGURE 5 shows a separability measurement in which a tube with a fixed distance and a tube with a variable distance were measured (**FIGURE 3**, test A). This test can be interpreted as a calibration step in order to define which specific separability must be parameterized in the sensor model. A characteristic feature of such a measurement is the blurring and merging of two objects into a single object if the relative distance of the moving tube to the sensor is similar to the fixed distance of the partner tube to the sensor. It can be seen that both the simulated amplitude and the measurement point distribution were always in the same value range. The conclusion from this was that the model recognizes objects that are close together just as precisely as the real sensor. This observation can be helpful with regard to the parameterization of the sensor model, but in particular the combination of the number of beams, echoes, etc. It is thus possible to design the sensor algorithms in such a way that corresponding objects can be distinguished.

The benefit for sensor manufacturers is that they can test a wide range of sensor settings and parameter variants against each other and against an idealized model. In addition, tests of complex user scenarios are possible which can only be carried out with enormous effort or cannot be reproduced in the real world. From a developer's point of view, the corner case search is also helpful here. Corner cases refer to recurring, unfavorable situations during parking, which are then evaluated with regard to the processing algorithm to be executed. Typically, the model output of ideal sensor models does not provide the necessary depth of environmental resolution and level of detail for corresponding investigations.

CONCLUSION

The joint project aimed at the validation of the ultrasonic sensor model regarding all relevant effects that are featured in a real ultrasonic sensor. In addition, proof was to be provided that a real sensor can be mapped realistically in the CarMaker simulation environment. For this purpose, the ray tracing-based sensor model Ultrasonic RSI was used which enabled access to the raw sensor data. In order to validate typical effects of ultrasonic sensors, a detailed test catalog was designed, and corresponding measurements were carried out. At the end of the successful implementation of the project, a validated and verified ultrasonic sensor model with a high degree of maturity was available, which Continental is now able to use for its development and customer activities. This means that ultrasonic sensor models with a very high level of detail are now available in the simulation environment for development, testing and application, helping to improve the functionality of driver assistance systems at an early stage.