BRNO UNIVERSITY OF TECHNOLOGY FACULTY OF INFORMATION TECHNOLOGY

Excel@FIT 2026
http://excel.fit.vutbr.cz

# Virtual testing of ADAS in a statistically defined operational design domain

Vít Mořkovský

**Abstract**
This work proposes an adaptive approach for the safety validation of Advanced Driver Assistance Systems (ADAS) under conditions that better reflect real-world operation than standard evaluation approaches. The method uses Bayesian Optimization (BO) to efficiently identify critical scenarios and explore the boundary between safe and unsafe system behavior. It is validated on a custom Automatic Emergency Braking (AEB) system that combines IPG CarMaker® simulation with custom-developed decision and control logic. The main contribution is a testing framework that extends AEB evaluation beyond idealized European New Car Assessment Programme (Euro NCAP) conditions and supports a more realistic assessment of system behavior in non-ideal conditions, such as low visibility and low tire-road friction. The results show that the proposed framework can efficiently identify critical scenarios and reveal system limitations.

*xmorko03@stud.fit.vut.cz , *Faculty of Information Technology, Brno University of Technology*

## 1. Introduction

Advanced driver assistance systems (ADAS) are becoming an integral part of modern vehicles, creating an increasing demand for reliable and systematic testing methodologies. Currently, these systems are primarily evaluated according to NCAP [1]. Although this methodology provides an important basis for assessment, it considers only a limited set of scenarios and is generally performed under ideal environmental conditions. Therefore, this solution does not constitute an efficient and sufficiently representative approach for the testing of complex systems. One of the central challenges in ADAS testing is the development of an efficient method for generating and selecting test scenarios. The current NCAP approach relies on exhaustive grid sampling, which scales poorly with the number of dimensions. An effective testing methodology should therefore ensure systematic coverage of the parameter space and targeted exploration of its most critical regions.

This work therefore proposes a general methodology for scenario selection in ADAS testing. The proposed approach is based in the adaptive selection of new scenarios using a probabilistic surrogate model and acquisition functions. This enables the selection of new simulations based on the predicted system behavior and the associated model uncertainty.

The proposed methodology is demonstrated on a custom Automatic Emergency Braking (AEB) system implemented as an external module coupled with the IPG CarMaker® simulation environment. The system makes decisions based on images obtained from a virtual front camera. This setup was chosen to analyze the scenario selection process under varying vehicle speed, visibility, and tire–road friction conditions. For example, the vehicle speed interval considered of 30 to 100 km/h was defined with respect to the NCAP framework and the statistical distribution observed in the available traffic data.

## 2. Scenario Selection Method

The generation of test scenarios for ADAS systems represents a complex task. Therefore, the proposed approach builds on a methodology used in current testing practice. Compared with the original approach, this methodology was extended by an additional layer describing environmental conditions. Scenarios are represented using four basic layers, as schematically shown in Fig. 1.1. The parameter ranges defining the ODD are selected based on a statistical analysis of available data, for example, the observed distribution of vehicle speed. The introduction of the fourth layer is motivated by the characteristics of the sensor, the characteristics of the vehicle handling, and the model of description of the five-layer scenario [2].

## 3. Adaptive Search for Scenario Generalization

Due to the high computational cost of simulations (or potentially real-world tests), an exhaustive grid-based search of the parameter space was not performed. As the number of considered parameters increases, such an approach would lead to an excessively large number of test cases. Therefore, an adaptive Bayesian optimization method was used to select new scenarios, as illustrated in Fig. 2.1.

The method employs a probabilistic surrogate model implemented as a Gaussian process that approximates system behavior in previously unexplored regions of the parameter space using already evaluated scenarios. In addition to an estimate of the expected output, the model also provides a measure of prediction uncertainty. This information is then used by acquisition functions to identify new scenarios with the highest value for further analysis.

The entire process is iterative. First, an initial set of scenarios is selected and simulated in the IPG CarMaker® environment. Based on the obtained result, a surrogate model is constructed, and new test points are then selected using acquisition functions. This procedure is repeated until the boundary separating safe and critical system behavior is sufficiently refined. In the presented AEB application, the surrogate model is implemented as a Gaussian Process regressor with a Constant Matern kernel [3]. The surrogate model is updated using the observed outcome of each simulated scenario, expressed as a binary failure indicator (crash / no-crash). The adaptive search procedure combines three acquisition functions. The first acquisition function selects scenarios with the highest surrogate uncertainty, the second focuses on refining the transition between safe and unsafe behavior, and the third prioritizes regions with an increased likelihood of failure [3]. Compared to the article, a variant without the failure regions sampling acquisition function was also tested, together with updating a computationally cheaper surrogate model.

The adopted approach makes it possible to concentrate simulations in regions of high uncertainty and near the failure boundary, rather than uniformly sampling the entire space. This significantly reduces the number of required simulations while preserving the ability to identify critical scenarios and characterize the overall parameter space.

## 4. Developed Emergency Braking System and Simulation Environment

To validate the proposed methodology, a simplified emergency braking system was implemented in the IPG CarMaker® environment. The system operates on images acquired from a virtual front camera, from which object positions and distances are estimated using object detection and homographic transformation. Based on the estimated distance and ego-vehicle speed, the time-to-collision is computed and used to trigger emergency braking. The simplified AEB decision logic is illustrated in Fig. 3.1 [4], while the overall system architecture and its interaction with the IPG CarMaker® simulation environment are shown in Fig. 3.2. In contrast to the predefined AEB implementation, the proposed system is based on virtual camera perception rather than direct access to the positions of surrounding traffic participants.

## 5. Main Contributions and Conclusion

This work presents an adaptive methodology for virtual testing of ADAS based on surrogate modeling and Bayesian optimization. The proposed approach enables efficient identification of the boundary between safe and unsafe system behavior while reducing the number of required simulations. The adaptive scenario selection process is illustrated in Fig. 4.1. The evolution of the predicted pass rate is shown in Fig. 4.2. The quantitative results are summarized in Table 4.1. Validation on a simplified camera-based AEB system in the IPG CarMaker® environment showed that the framework can effectively reveal system limitations under non-ideal operating conditions.

## Acknowledgements

I would like to express my sincere gratitude to the supervisor of my Master's thesis, Ing. Jiří Novák, Ph.D., for his professional guidance, supportive approach, valuable advice, and for providing beneficial consultations. I would also like to thank the members of the Aeroworks research group for their support and collaboration.

Results presented in this work were co-financed from the state budget by the Technology Agency of the Czech Republic under the programme: 12th Public Competition Programme for the Support of Industrial Research and Experimental Development TREND, PP1. The research was carried out within the grant project FW12010130 - Multi-modal Validation System Simulator for Autonomous Driving.

# References

[1] Euro NCAP. Car safety protocols. online, 2026. Available at: `https://www.euroncap.com/protocols/`. [cit. 2026-04-12].

[2] Sebastian Karl Wagner. *Efficient scenario-based assessment of automated driving systems through virtual testing*. PhD thesis, Technische Universität München, 2021.

[3] Robert J. Moss, Mykel J. Kochenderfer, Maxime Gariel, and Arthur Dubois. Bayesian safety validation for failure probability estimation of black-box systems. *Journal of Aerospace Information Systems*, 21(7):533–546, July 2024.

[4] MathWorks. Autonomous emergency braking with sensor fusion. online, 2021. Available at: `https://www.mathworks.com/help/driving/ug/autonomous-emergency-braking-with-sensor-fusion.html`. [cit. 2026-04-13].