Letters

Development and Testing of Advanced Driver Assistance Systems Through Scenario-Based Systems Engineering

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***Abstract*—Advanced driver assistance systems (ADAS) hold great promise for improving transportation safety and efficiency. However, the development of these technologies requires a robust and systematic engineering process to ensure their reliable and safe operation in various traffic situations. In this letter, we present a scenario-based systems engineering for the development and test of advanced driver assistance systems, drawing insights from a real automotive proving ground. This letter is the second part of Decentralized and Hybrid Workshop (DHW) on Scenarios Engineering (SE), which aims to improve scenario diversity and representation for advanced driver assistance systems. The article proposes a 5-layer scenario architecture and also describes several key tasks that must be addressed in the ADAS, such as lane keeping assistance (LSK), adaptive cruise control (ACC) and autonomous emergency braking (AEB). Additionally, we elaborate on the testing challenges that the aforementioned tasks entail. Finally, we employ clustering methods to obtain 9 crucial scenarios of LKA, which can be utilized for ADAS testing.**

***Index Terms*—Scenarios-based system engineering, advanced driver assistance systems, parallel intelligence, lane keeping assistance, adaptive cruise control, autonomous emergency braking.**

I. Introduction

ADVANCED driver assistance systems (ADAS) and autonomous driving technologies [1], [2] have the potential to improve safety, traffic flow, environmental sustainability, and the overall driver experience. However, the development and testing of these technologies involve several main issues [3], [4], such as ensuring their reliability, robustness, and safety in real-world traffic scenarios. Scenarios-based system engineering (also named "Scenarios Engineering" [5], [6]) has emerged as a promising approach to address these issues by systematically identifying, constructing and testing a set of critical scenarios that are representative of the real-world conditions in which the autonomous driving functions will be calibrated and verified.

SE [7], [8] uses trusted, effective, advanced scenarios [9], [10], [11] to ensure autonomous driving functionality and performance. It was inspired by parallel intelligence (PI) [12], [13], digit twin (DT) [14], [15] and virtual reality (VR). SE is a novel approach that integrates scenarios and activities within a specific temporal and spatial range to design, certify, and verify actionable AI. They can be concrete or abstract, real, virtual [16], [17], [18], parallel [19], or any intermediate options [20], [21], [22]. The SE developing autonomous driving functions involves the following steps: (1) Scenarios identification; (2) Test case generation; (3) Establishing performance evaluation indexes, goals and metrics; (4) Iterative calibration and certification; (5) Verification and validation.

The development of advanced driver assistance systems using a scenarios-based system engineering approach entails various research challenges [23], [24], [25] pertaining to perception, decision making, and control. Addressing these challenges is crucial to ensure the effectiveness and efficiency of the approach. The identified challenges encompass lane keeping assistance, adaptive cruise control and autonomous emergency braking. To evaluate and demonstrate the capabilities of the approach, a dedicated proving ground serves as the primary test environment, as illustrated in Fig. 1. The testing ground encompasses a road area of approximately 195,000 square meters, accompanied by a building area spanning approximately 90,000 square meters. These facilities often encompass specific test areas such as highways, urban settings, rural roads, and more. Notably, the high-speed simulation ring boasts a length of 2,876 meters. Additionally, a long straight performance test track measuring 1,400 meters allows for assessments at a maximum design speed of 180 km/h, suitable for conducting tests related to lane keeping assistance (LKA) [26], [27], adaptive cruise control (ACC) [28], [29], autonomous emergency braking (AEB) [30], [31], and

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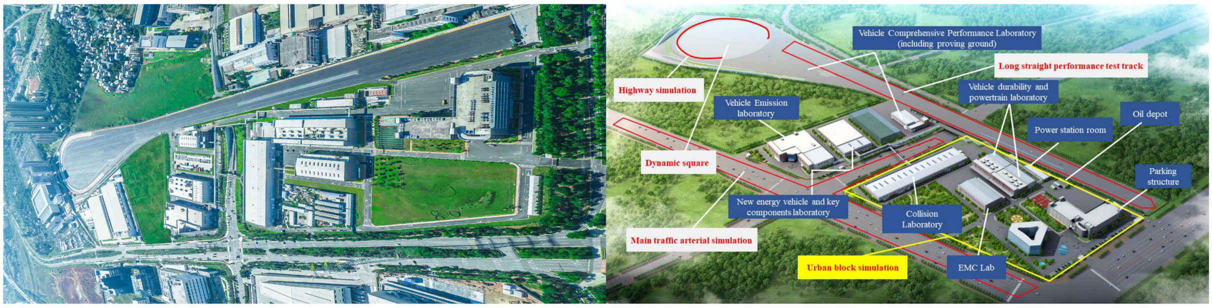

Fig. 1. Proving ground at China automotive technology and research center automotive test center (Guangzhou). (Left) real proving ground; (Right) proving ground specific function.

forward collision warning (FCW). Collectively, these advanced driver assistance systems contribute to improving overall vehicle safety, reducing the risk of accidents, and enhancing the driving experience by providing assistance and warnings to the driver in critical situations.

In this context, the scenarios-based system engineering approach offers an effective solution to address the above perception, decision making, and control-related research challenges presented in developing ADAS. Consider this, we divide the method into five layers [32], [33]: including, road layer, traffic infrastructure layer, traffic participant layer, additional condition layer, and simulation layer. By creating diverse and representative testing scenarios, developers can design and validate ADAS for a wide range of driving conditions. The main contributions of this article are as follows:

Firstly, this article provides an effective five-layer architecture for the development and validation of ADAS, ensuring that they meet high safety standards and test reliably in a range of driving scenarios.

Secondly, this article provides empirical support for the efficacy of the proposed methods through the use of various illustrative examples. Furthermore, the article includes critical test scenarios for various ADAS, which enhances the credibility and relevance of the research.

Thirdly, the effectiveness of this method in constructing LKA testing scenarios has been demonstrated through computational experiments. The experiments have confirmed the efficiency achieved by employing 9 representative testing scenarios, thereby validating the rationality of existing standards and policies.

The remainder of this article is structured as follows. In Section II, the five-layer architecture of scenarios-based system engineering is described in detail. Sections III, IV and V discusses several key tasks that must be addressed in ADAS, such as LKA, ACC and AEB. Section VI presents a case study. Conclusion is drawn in Section VII.

II. Detailed Implementation of Scenarios-Based System Engineering for Advanced Driver Assistance Systems

Advanced driver assistance systems play a pivotal role in enhancing road safety, comfort, and efficiency. With the increasing complexity and capabilities of ADAS technologies, it is essential to establish a robust testing framework that can comprehensively evaluate their functionality, performance, and interoperability. This section focuses on the detailed implementation of scenarios-based system engineering as a means to accomplish this objective.

A. Brief Introduction Scenarios - Level of Abstraction

1) Functional Scenarios: A representation of scenario space at a semantic level utilizing linguistic notations is employed [34], [35]. The vocabulary employed for describing functional scenarios is tailored to the specific use case and domain, allowing for varying levels of detail. The functional scenarios should encompass various driving conditions, such as different weather conditions, road types, and traffic densities.

2) Logical Scenarios: A state-space level representation of the scenario space is utilized, wherein each parameter corresponds to an influential factor. The parameter ranges within the state space are defined, providing a comprehensive characterization of the scenario space [36], [37]. Optionally, probability distributions can be specified to represent the parameter ranges. Furthermore, the interdependencies between parameter ranges can be specified through correlations or numeric conditions if desired.

3) Concrete Scenarios: A parameterized depiction characterizes each scenario, where concrete scenarios are instantiations of logical scenarios with assigned values for each parameter [38], [39], [40]. Concrete scenarios provide a detailed representation of real-world driving situations, including specific environmental conditions, road layouts, and traffic patterns. These scenarios involve precise vehicle speed, GPS coordinates, road markings, traffic light states, and the behavior of surrounding vehicles and pedestrians.

B. The Framework of Scenarios-Based System Engineering for Advanced Driver Assistance Systems

In order to effectively describe and represent traffic scenarios within the knowledge domain, hierarchical models have been widely adopted by experts and scholars. For instance, the connected and automated vehicles scenario library adopts a 5-layer model, with the third layer specifically emphasizing temporary traffic facilities such as temporary road signs. The Association for Standardization of Automation and Measuring

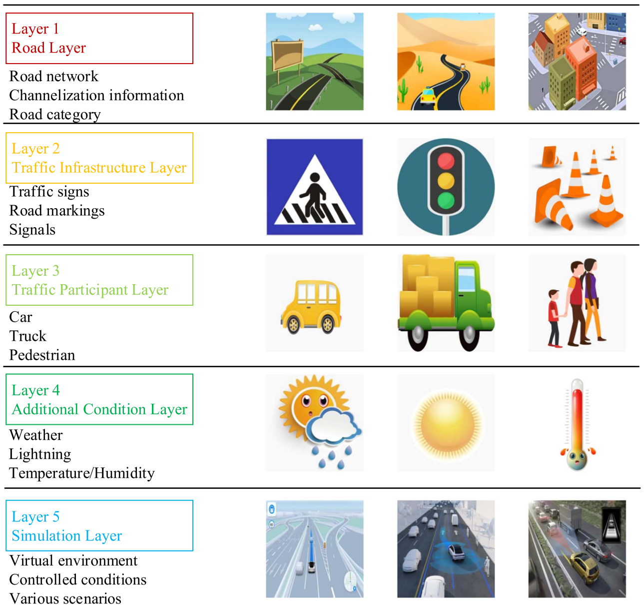

Fig. 2. Five layer representation of the traffic scenario.

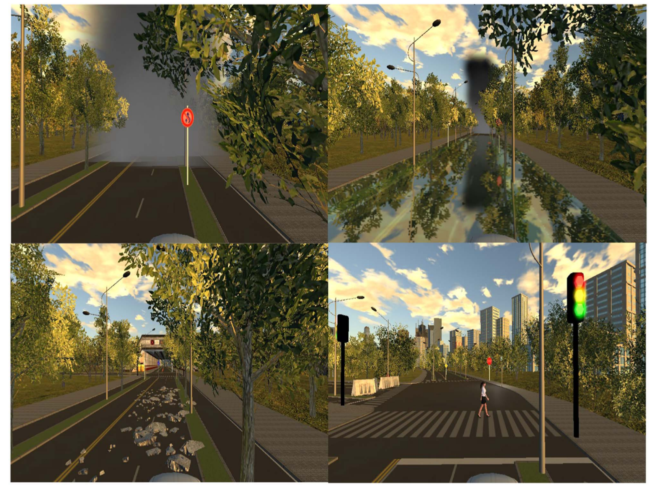

Fig. 3. Examples of diverse testing scenarios generated by virtual environment. Best viewed with zooming.

Systems (ASAM) [41], [42] puts forth a 6-layer scenario model as part of the PEGASUS project carried out from 2016 to 2019.

Numerous significant technological advancements, including foundation models, 6G, digital twins (DT), Internet of Things (IoT), Cyber-Physical-Social Systems (CPSS), cobots, edge computing (EC), and blockchain, have been seamlessly integrated with Scenarios Engineering to enhance the intelligence and personalization of related applications. In this rapidly evolving landscape, we propose a comprehensive 5-layer division of traffic scenarios, providing a structured framework for scenario analysis and development, as shown in Fig. 2. This framework encompasses the following layers: the road layer, the traffic infrastructure layer, the traffic participant layer, the additional condition layer, and the simulation layer. Layer 1, as the road level, encompasses the overall road environment, encompassing essential elements such as road network topology and channelization information. This layer serves as the cornerstone for constructing high-definition (HD) map information, enabling precise mapping and localization. Layer 2 focuses on static and dynamic traffic facilities, encompassing a wide range of infrastructure components and features. This layer includes traffic signs, signals, road markings, and other essential elements that influence traffic behavior and regulation. Layer 3 captures the dynamic and static information of various types of vehicles and pedestrians, forming the traffic participant layer. It accounts for the diverse characteristics and behaviors exhibited by different traffic entities, providing a detailed representation of their movements, positions, velocities, and interactions. Layer 4 expands the scope to encompass additional conditions that impact the described scenario, such as weather conditions, lighting levels, temperature variations, and humidity levels. This layer ensures a comprehensive representation of the environmental context, facilitating more accurate assessments and analyses. Finally, layer 5 represents the simulation layer, providing a virtual environment to simulate and evaluate traffic scenarios. By leveraging advanced computational techniques, this layer enables the analysis of complex scenarios, the validation of algorithms, and the testing of various scenarios under controlled conditions, as shown in Fig. 3. The proposed 5-layer division of traffic scenarios offers a comprehensive and systematic approach to scenario representation and analysis. By considering multiple layers of information, encompassing the road environment, traffic facilities, participants, additional conditions, and simulation capabilities, this framework enhances the understanding and modeling of real-world traffic scenarios, facilitating the design, development, and evaluation of ADAS and related applications.

III. Lane Keeping Assistance and Its Key Testing Scenarios

Lane keeping assistance is an advanced driver assistance system that aims to enhance vehicle safety by assisting drivers in maintaining their vehicles within the boundaries of a lane. LKA utilizes a combination of sensors, such as cameras and radars, to detect lane markings and monitor the vehicle's position relative to them. Based on this information, the system provides corrective actions, typically in the form of gentle steering interventions, to keep the vehicle centered within the lane. Lane keeping assistance employs various computer vision algorithms for road edge detection. For instance, the probabilistic hough transform is a variant of the hough transform algorithm that detects line segments rather than complete lines. Here is the formula for the probabilistic hough transform for line detection:

$$\rho = x^{\star} \cos(\theta) + y^{\star} \sin(\theta) \tag{1}$$

For each sampled point (x, y), compute the corresponding ρ and θ values.

To ensure the effectiveness and reliability of LKA, some testing scenarios encompass a wide range of real-world driving situations and challenges that LKA must proficiently handle.

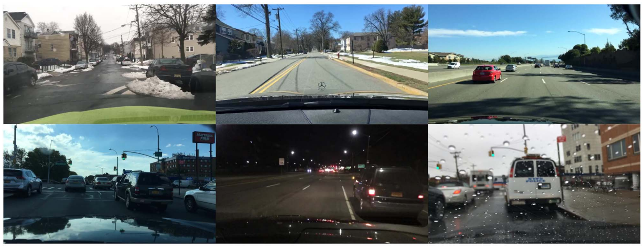

Fig. 4. Example of testing scenarios of lane keeping assistance. Best viewed with zooming.

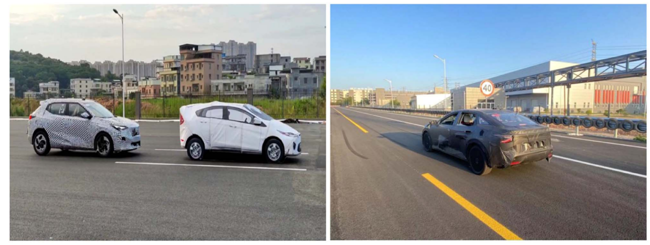

Fig. 5. Example of testing scenarios of adaptive cruise control. Best viewed with zooming.

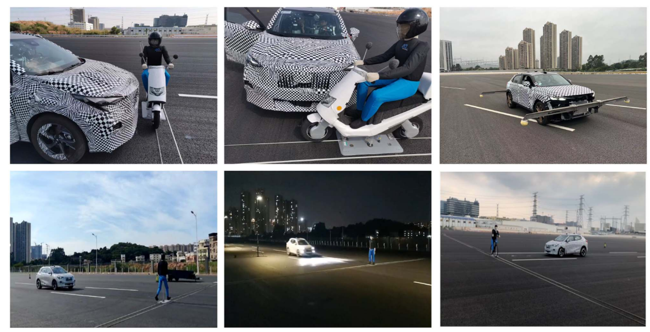

Fig. 6. Example of testing scenarios of autonomous emergency braking. Best viewed with zooming.

Some key testing scenarios (see Fig. 4) for LKA include: Lane Changes: this scenario tests the system's ability to detect lane changes, assess the surrounding traffic, and execute appropriate steering interventions to ensure a seamless transition. Curves and Turns: this scenario assesses the system's capability to adjust steering angles, maintain appropriate lane position, and provide necessary assistance to the driver during the maneuver. Road Marking Variations: testing the system's response to different types of road markings, including faded or obscured markings. Adverse Weather Conditions: assessing the system's performance in adverse weather conditions such as rain, fog, or snow. High-Speed Scenarios: this scenario assesses the system's effectiveness in maintaining lane position while ensuring the safety of the vehicle and its occupants under high-speed driving conditions.

IV. Adaptive Cruise Control and Its Key Testing Scenarios

Adaptive cruise control is an advanced driver assistance system [43], [44] designed to enhance driving comfort and safety by automatically adjusting the vehicle's speed to maintain a safe distance from the preceding vehicle. Unlike conventional cruise control systems, ACC utilizes radar or sensor technology to monitor the distance and relative speed of the vehicle ahead. Based on this information, ACC can automatically adjust the vehicle's speed, acceleration, and braking to maintain a desired gap and follow the flow of traffic. Here is commonly used gap control algorithm in ACC along with their corresponding formulas:

$$D_{des} = T_{des} * V \tag{2}$$

Calculate the desired distance D_{des} between the ego vehicle and the target vehicle based on the desired time headway T_{des} and the target vehicle's velocity V.

To ensure the effectiveness and reliability of ACC, a comprehensive set of testing scenarios is essential. Some key testing scenarios (see Fig. 5) for ACC include: Highway Driving: this scenario assesses the system's ability to maintain a safe following distance and smoothly adjust speed to match the flow of traffic. Stop-and-Go Traffic: evaluating ACC's behavior in congested traffic situations where frequent acceleration and deceleration are required. Interaction with Other Vehicles: this scenario assesses the system's ability to adjust speed and maintain safe distances during complex traffic interactions.

V. Autonomous Emergency Braking and Its Key Testing Scenarios

Autonomous emergency braking is an advanced safety feature in vehicles [45], [46] that is designed to mitigate or prevent collisions by automatically applying the brakes in emergency situations. The system can detect obstacles, pedestrians, or vehicles in the vehicle's path and activate the brakes to reduce the severity of a collision or avoid it altogether. The collision risk assessment: is calculated as follows:

$$TTC = Di/v_{rel} \tag{3}$$

Calculate the time-to-collision TTC between the vehicle and the detected object based on their relative velocity v_{rel} and the distance Di.

To ensure the effectiveness and reliability of AEB systems, some scenarios [47] simulate real-world driving situations and evaluate the system's performance, responsiveness, and ability to detect and respond to potential collision risks. The key testing scenarios (see Fig. 6) for AEB include: Pedestrian and Cyclist Detection: this scenario assesses the system's ability to identify vulnerable road users, predict their movement patterns, and apply braking interventions to prevent or reduce the severity of collisions. Rear-End Collisions: this scenario assesses the system's capability to detect slowing or stationary vehicles ahead and initiate braking interventions to avoid or mitigate rear-end collisions. Obstacle Detection: testing AEB's performance in

TABLE I
EXPLORING THE FINDINGS OF CLUSTERING

Elements	Element category	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9	Total
Obstruction	W/	8	22	6	14	10	7	7	2	3	79
	W/o	14	36	11	4	16	5	20	15	0	121
Weather condition	Sunny/Cloudy	17	51	14	3	0	0	16	4	0	105
	Overcast	5	7	3	7	7	3	11	5	1	49
	Rain/Fog/Haze	0	0	0	8	19	9	0	8	2	46
Time	Daytime	1	53	8	15	14	0	24	0	0	115
	Dusk	5	5	2	3	5	1	3	7	0	31
	Night	16	0	7	0	7	11	0	10	3	54
Type of lane lines	Straight	10	39	15	14	19	11	16	12	0	136
	Curved	12	19	2	4	7	1	11	5	3	64
Color of lane lines	White	15	48	14	16	23	10	18	8	1	153
	Yellow	7	3	3	1	2	1	8	9	2	36
	Other	0	7	0	1	1	1	1	0	0	11
Vehicle speed	<30km/h	0	0	0	0	0	0	8	4	0	12
	30–40km/h	0	0	0	0	0	0	13	11	0	24
	40-50km/h	7	6	0	0	5	0	6	2	0	26
	50-60km/h	9	14	0	0	17	0	0	0	2	42
	60-70km/h	5	31	0	0	4	2	0	0	1	43
	70-80km/h	1	7	0	3	0	6	0	0	0	17
	80-90km/h	0	0	2	13	0	3	0	0	0	18
	90-100km/h	0	0	9	2	0	1	0	0	0	12
	>100km/h	0	0	6	0	0	0	0	0	0	6
Location	Highways	5	18	10	12	0	7	2	6	2	62
	Regular roads	6	16	7	6	10	5	12	7	1	70
	Urban/Rural roads	11	24	0	0	16	0	13	4	0	68
State of lane lines (fade)	W/	8	9	6	2	6	5	10	5	1	52
	W/o	14	49	11	16	20	7	17	12	2	148
Total of each group	Number	22	58	17	18	26	12	27	17	3	200
	Proportion	11.00%	29.00%	8.50%	9.00%	13.00%	6.00%	13.50%	8.50%	1.50%	100.00%

detecting and responding to stationary objects or obstacles in the vehicle's path, such as parked vehicles, road debris, or barriers.

VI. EXPERIMENTAL EVALUATION

This section presents experimental evaluation of our proposed method for identifying critical test scenarios for the lane keeping assistance, based on the analysis of 200 instances of LKA failure scenarios. The 200 scenarios are gathered from real-world driving scenarios. The data is collected from various sensors, recording the vehicle's position, orientation, and speed under diverse conditions such as weather, road type, traffic density, and vehicle speed. The present experiments introduce a novel approach that encompasses the utilization of the analytic hierarchy process (AHP) and hierarchical clustering (HC) to identify critical test scenarios for the comprehensive evaluation of LKA. The squared Euclidean distance d_{ij} between the i th sample and the j th sample is calculated as follows:

$$d_{ij} = \sum_{k=1}^{m} \left|X_{ij} - X_{jk}\right|^2 \tag{4}$$

where m denotes the number of variables in each sample and X_{jk} is the measurement value of the k th variable in the i th sample.

Subsequently, a comprehensive compilation of the clustering results for the 200 failure scenarios was obtained based on the agglomeration schedule, as tabulated in Table I. This experiment is essential for developing LKA that can perform well under various driving conditions [48], [49]. It provides valuable insights into the critical factors that affect LKA performance and offers a more comprehensive evaluation of AV, which can help improve their safety and reliability.

VII. CONCLUSION

In conclusion, this letter presents a scenario-based systems engineering approach for the development and testing of ADAS. By proposing a comprehensive 5-layer scenario architecture and addressing key challenges in ADAS development [50], [51], [52], we provide a structured framework for scenario analysis and development. The experiments conducted validate the system's capability to develop LKA and emphasize the importance of scenario diversity and comprehensive testing in ensuring reliable and safe LKA operation. This work contributes to the advancement of ADAS technologies and paves the way for improved transportation safety and efficiency.

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