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Defining Reasonably Foreseeable Parameter Ranges Using Real-World Traffic Data for Scenario-Based Safety Assessment of Automated Vehicles

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ABSTRACT Verification and validation of automated driving systems' safety are some of the biggest challenges for the introduction of automated vehicles into the market. Scenario-based safety assessment is an efficient and repeatable method to test the systems' safety before their deployment in the real world. However, even with limited traffic situations identified as critical to the system behavior, there is still an open range of parameters to describe each situation. Thus, defining specific parameter ranges is crucial to realize the scenario-based safety assessment approach. This study proposes a method to parameterize scenarios extracted from real-world traffic data, analyze their distribution and correlation, and incorporate them into the definition of reasonably foreseeable parameter ranges through the contextualization of resulting ranges with reasonable risk acceptance thresholds from different fields and international environments. Representative values can be selected from these specific parameter ranges to extract specific concrete scenarios applicable for the systems safety assessment. The applicability of the proposed method is demonstrated using parameter ranges obtained to define two sets of 960 cut-in and 6,442 deceleration scenarios extracted from a new set of traffic data collected from Japanese highways under the SAKURA initiative. The outcomes will enable comparisons with traffic data from other countries and inform automated driving system developers, standardization bodies, and policymakers to develop automated vehicle safety assessments applicable internationally.

INDEX TERMS Automated vehicles, traffic data analysis, event detection, logical scenarios, risk acceptance, safety, highway, verification and validation methods, naturalistic driving data.

I. INTRODUCTION

A. MOTIVATION

Automated driving systems (ADS), under their operational domain, shall not cause reasonably foreseeable and preventable traffic accidents [1]. Appropriate guidelines and methodologies that consider reasonably foreseeable and preventable traffic situations have been proposed to evaluate ADS safety and readiness to operate in real-world traffic. One such effort is the scenario-based testing approach that aims to generate a limited number of critical test cases from an unlimited number

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of real-world situations for system verification and validation [2]–[6].

A growing body of literature recognizes the importance of addressing how to find the set of representative scenarios for the scenario-based testing of ADS [7]–[13]. However, most prevalent research focuses on one or some aspects within the scenario-based approach. Currently, there is no methodology to support a scenario generation process that uses a specific data source to build a scenario database from specific testing scenarios selected and executed for ADS assessment. This study proposes a method to address the previously mentioned issue through the incorporation of a reasonably foreseeable perspective, defined as *forecastable by experts examination of real-world data and evidences, or by attentive human drivers in situ* [14], to select the most representative test cases to evaluate ADS safety and behavior in the specified range [15], [16].

To realize the scenario-based approach from the standpoint of reasonably foreseeable events, we incorporated the frequency of real traffic situations to define reasonably foreseeable scenarios based on predefined risk exposure standards [23], [24]. The fundamental of our method resides in the availability of real-world driving data. Selected scenarios can be extracted from this data to generate logical scenarios defined with kinematic parameter ranges. Real-world driving data collected with infrastructure sensors, drones, and test vehicles has long been used as sources to generate scenarios for the safety assessment of driver assistance and automated driving systems [17], [18]. Hence, real-traffic monitoring and naturalistic driving data collected from Japanese highways between 2017 and 2020 as a data source were used for this study.

B. RELATED WORK

Numerous safety-assessment approaches exist to assess the functional and operational safety of ADS [19]–[22]. One evaluation concept implements ADS that can outperform humans by a defined factor, such as a particular test on miles/kilometers to be driven by the automated vehicle (AV). The underlying assumption being AVs subjected to such evaluations will reduce the current figure of road traffic crashes [23]. Nevertheless, road traffic crashes are still occurring at high rates; accordingly, the expected reduction of accidents by ADS is unclear. Nonetheless, this evaluation method implies that ADS may be introduced in the real world, provided they cause fewer accidents than a human driver [24]. However, it is infeasible to obtain a statistically valid argument for real-world tests due to the required distance to be driven by the AV [25].

Previous research developed an approach to conduct a passive form of real-world testing for ADS assessment. In this approach, the automated driving function is installed in an actual testing vehicle and provided with the real-world inputs of the sensors, without access to the actuators of the test vehicle, i.e., the so-called shadow mode testing [10]. The system's performance can then be evaluated based on its decisions toward real traffic situations. However, hazardous situations created by the surrounding traffic are not the only safety issue the AV encounters; hazards created by the inappropriate action of the AV and interaction with its users also have detrimental impacts on traffic safety [26], [27]. To clarify, the actual actions of the AV directly influence how AV users and other road users act and interact with the AV on the road and may be different from passive actions. Consequently, the results are limited to system validation [28].

Another safety-assessment approach is to limit the Operational Design Domain (ODD) to the minimum extent, such as a closed test track and a well-controlled roadway with the maximum safety measures [29]. Once traffic situations are significantly reduced, they can accurately conduct ADS safety validations in a safe, economical, and feasible way [30]. Following the safety assessment result, the ODD can gradually be increased. Although such a staged introduction of AV is promising and currently adopted by international regulations for Automated Lane Keep Systems (ALKS), there is a risk of automated driving vehicles affecting the frequency of scenario occurrences as well as the likelihood and severity of road traffic crashes [31], [32]. To address these limitations, researchers proposed a traffic-simulation-based approach through the development of a framework to simulate an extensive road network with hundreds of vehicles and pedestrians to investigate the effects of ADS on overall traffic safety [33], [34]. Nevertheless, these approaches are not deemed suitable for fully automated driving vehicles, which lack fallback drivers and operate in an unlimited ODD.

Scenario-based safety approaches have been primarily applied to evaluate the safety of complex systems in aviation and nuclear power plants [35], [36]. Similar testing principles have also been developed to test drones [37]. In the automotive domain, the scenario-based approach models the interaction between the subject vehicle and the surrounding traffic participants and objects. This modeling attempts to categorize and structure the complex real-traffic patterns into a finite number of manageable patterns (i.e., functional scenarios) and parametrize each pattern with the corresponding variable ranges (i.e., logical scenarios). From the defined logical scenarios, specific combinations of values are extracted (i.e., concrete scenarios) and applied for ADS safety assessment. National projects worldwide [38]–[42] adopted this approach to assess the ADS performance as a complement to Functional Safety [19], Safety of the Intended Functionality (SOTIF) [20], Objects and Events Detection and Response (OEDR) [21], [22], and Cybersecurity [43].

Focusing on functional scenarios that can provide meaningful information for the ADS development and safety validation, scenario-based testing aims to reduce the test scope and induce critical ADS behavior. However, the traffic environment is an open parameter space; thus, logical scenarios may assume indefinite parameter ranges even with limited operational domains, such as highways, and

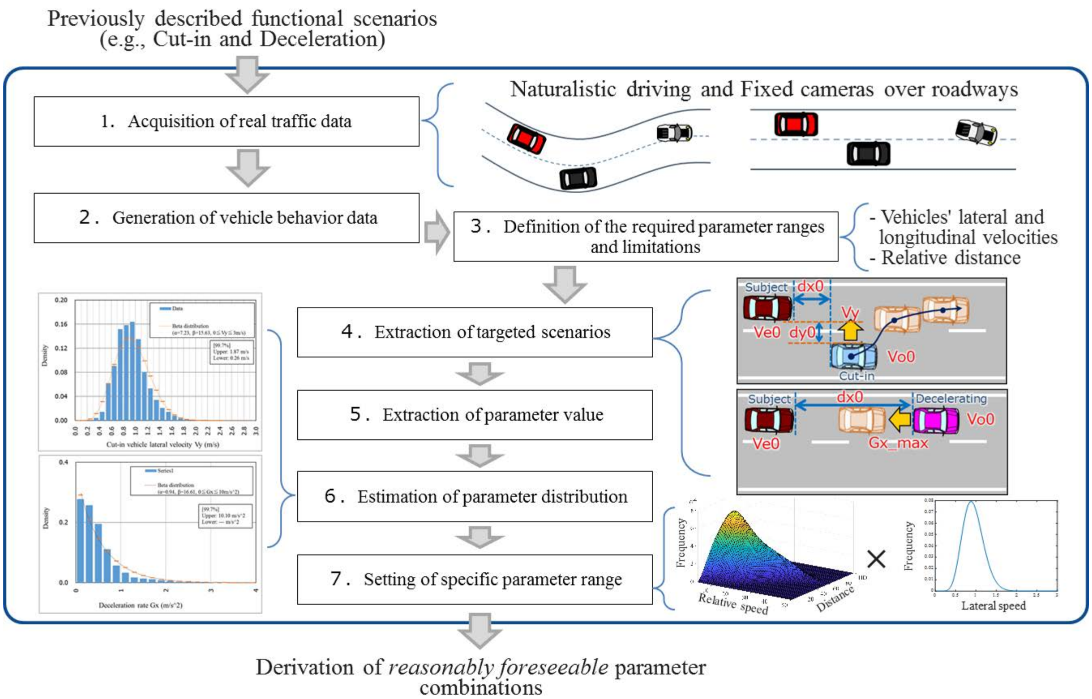

FIGURE 1. Steps of the proposed method and study approach.

limited typical functional scenarios. For example, cut-in or deceleration scenarios may occur with an extensive range of relative distance and velocity parameters. It is challenging to decide which range needs to be considered in scenario-based testing and how it can be defined for ADS safety validation. This study attempts to specify accident-free range through the definement of a specific border of reasonably foreseeable parameter ranges where the ADS must perform safely.

Defining preventable ranges, which incorporate avoidable events achievable by a competent and careful human driver and state-of-the-art technology, is out of the scope of this study. Therefore, the data analysis does not include highly critical driver behaviors and crash or near-crash data.

C. RESEARCH CONTRIBUTION

This study contributes to the development of socially acceptable and reliable ADS safety assessment methodologies. The specific aim is three-fold:

1) To propose a method that parameterizes scenarios extracted from real-world driving data and later incorporates the results of parameters distribution and correlation into the definition of reasonably foreseeable parameter ranges.
2) To apply the proposed method to define parameter ranges for specific scenarios extracted from a traffic dataset collected in Japanese highways while providing detailed information to enable replication of the method in other countries/environments.
3) To contextualize the method proposed and the resulting parameter ranges with risk acceptance thresholds considered acceptable in different international environments and fields.

II. METHODOLOGY

Defining reasonably foreseeable parameter ranges for scenario-based testing enables the test to identify the most representative scenarios and determine the criticality of the scenarios based on specific parameter values, such as relative speed and distance. The proposed method implements sequential steps to process real-world traffic data to quantify and define reasonably foreseeable scenario parameter ranges considering the minimum risk acceptance, as illustrated in Figure 1.

1) Data acquisition is to acquire traffic data from a real-world driving traffic database. The method is applicable to various real-traffic data, such as naturalistic driving data from instrumented vehicle recordings, fixed roadway cameras, and drones.
2) Scenario generation is to produce vehicle behavior data to delineate the interaction between a subject vehicle and surrounding vehicles. Specific vehicle behaviors are preferably identified based on standardized methodologies. The selection process of specific functional scenarios is also specific to the scope of the study.
3) Scenario parameterization is to define the required parameter ranges and limitations to define the targeted logical scenarios based on the generated types of vehicle behaviors. A Logical scenario represents a functional scenario with representative vehicle parameter

ranges relative to surrounding traffic. Each parameter has a probability density of occurrence, and a distribution calculation notes the cross-correlation between parameters.

4) Scenario extraction is to extract the targeted scenes from the traffic data based on the defined parameter ranges that will identify and quantify the defined logical scenarios.
5) Parameter range evaluation is to extract parameter values that represent the behavior of all vehicles in the targeted logical scenarios. All parameters are defined and processed to extract and accumulate values for each parameter.
6) Parameters distribution and correlation are to estimate parameter distribution to analyze and determine correlations between different parameters. The parameter distribution characteristic is investigated to reach concrete scenarios defined with the exact parameter values.
7) Concrete scenarios generation is to set parameter ranges for concrete scenarios contextualized with risk acceptance thresholds considered acceptable in different international environments.

A. TRAFFIC DATA ACQUISITION

Data for this study were collected from real driving on limited-access highways in Japan. Highways from which the traffic data were collected are specifically designed to accommodate motor vehicles circulating at high speeds and controlled with tollgates where uninterrupted traffic may merge and leave only at selected locations. The data were acquired from three sources: 1) expert drivers who performed more than 1,047 hours of recorded driving on highways with an instrumented vehicle; 2) real-world traffic data recorded by fixed cameras over highways; and 3) averaged drivers who performed 350 hours of recorded driving on expressways using instrumented vehicles, as detailed in Table 1.

In Japan, there are two types of limited-access highways (see Appendix A in the supplementary material). Type-1 is an interstate highway known as the national expressway connecting prefectures [44]. Type-2 is an intra-city highway known as the urban expressway running above local roads in some of Japan's largest urban areas. For interstate highways, the legal speed limit is usually 100 km/h; however, most vehicles tend to drive at speeds between 100 and 120 km/h [45]. For intra-city highways, the speed limit is usually 80 km/h [46]. Traffic on these highways is usually denser than interstate highways; thus, the traffic may move significantly slower than the set speed limit. Such road traffic conditions and speed limits affected the speed range of the collected data, resulting in comparatively lower speed ranges.

B. SCENARIOS GENERATION AND PARAMETERIZATION

The current international efforts (e.g., ISO/WD 34502 [47]) to standardize an engineering framework and process of ADS scenario-based testing incorporate the possibility of

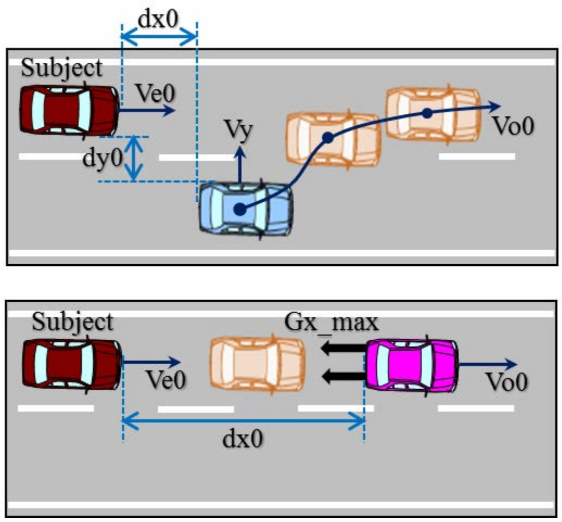

FIGURE 2. Cut-in (top) and deceleration (bottom) scenario models.

structuring a specific number of functional scenarios for highway-driving by considering different categories of AV actions: lane change and lane keep. Due to the difficulty of covering all described functional scenarios and practically exemplifying the proposed method's application, we focus on two critical scenarios: cut-in and deceleration. In both scenarios, a subject vehicle conducts a lane-keep on a multi-carriage highway, while a challenging vehicle cuts in or decelerates in front of it, as illustrated in Figure 2. The selection arises from the significant impact of these two scenarios on highway safety. In addition to the high-frequency occurrence and the potential safety impact of these scenarios, the selection also related to ease of such scenarios extraction from the data collected with infrastructure cameras and instrumented vehicles. The interaction occurs between two vehicles (i.e., a subject vehicle and a challenging vehicle).

A lane-keep cut-in maneuver involves two vehicles traveling in the same direction on two adjacent lanes when the preceding vehicle moves laterally from its lane toward the main lane of the following vehicle (subject vehicle), as shown in Figure 2-top. The extracted cut-in logical scenarios are described with the longitudinal velocity (Ve0) of the subject vehicle, longitudinal and lateral velocities (Vo0 and Vy respectively) of the cut-in vehicle, the relative velocity (Ve0-Vo0), and the initial longitudinal and lateral distances between vehicles (dx0 and dy0 respectively), as listed in Table 2. The parameters considered the initial value when a cut-in maneuver started except for the Vy, in which the maximum value was considered.

A lane-keep deceleration maneuver involves two vehicles traveling in the same lane and direction; it starts when the leading vehicle starts to reduce its speed constantly below the speed of the following vehicle (subject vehicle), as shown in Figure 2-bottom. A rear-end impact may occur if both vehicles continue traveling at the same speed range.

TABLE 1. Measurement tools characteristics and sensors set up for each data source used to collect the traffic data.

Attributes		Source-1	Source-2	Source-3
Producers		Instrumented Vehicle	Fixed Location Camera	Instrumented Vehicle
The main purpose of data acquisition		To collect driving behaviors of vehicles traveling on the expressway (within the instrumented vehicle's vicinity)	To collect driving characteristics at multiple points on the expressway	To understand regular driver behavior on the expressway (driving operations, visual actions, safety precautions when anticipating danger, etc.)
Data gathering period		Nov. 2018 to Mar. 2020	Jul. 2018 to Mar. 2020	Jan. 2017 to Mar. 2018
Data coverage areas		Metropolitan express way (Tomei/SHIN-TOMEI Expressway and Shimizu JCT-Tokyo IC)	Metropolitan express way (Daisan Keihin Road and Tomei Expressway)	14 locations in Japan (Hokkaido, Miyagi, Fukushima, Gunma, Saitama, Kanagawa, Nagano, Shizuoka, Mie, Aichi, Tokyo, Osaka, Hyogo, Fukuoka)
Number of lanes per direction		1-4	2-3	1-4
Road side construction		No	No	No
Traffic condition		Varying from free flowing to traffic jam	Varying from free flowing to traffic jam	Varying from free flowing to traffic jam
Weather condition		Sunny/cloudy/rainy/windy, no precipitation	Sunny/cloudy, no precipitation	Sunny/cloudy/rainy/windy, no precipitation
Data volume (hours)		2,968	31	350
Measurement tools	Lidar	360° (from 4 unites)	unavailable	unavailable
	Camera	360° (from 6-10 units)	2-4 units, Bird's-eye view, 360° (from building rooftops or overpasses)	360° (Front: 80°×3, Side: 120° x 2, Rear: 120°)
	Mobileye	Available	unavailable	available
Information processing		Vehicles and trajectory data are captured and extracted based on the Lidar cloud point data.	Vehicles and trajectory data are captured and extracted based on camera data.	Numerical data are acquirable for targets driving in front of the vehicle using Mobileye. Side and following vehicles' data are logically digitized.
Precisions		Target trajectory accuracy (Lateral: 10 cm; Longitudinal: 50 cm) ※Depends on the data state	Target trajectory accuracy (Lateral: 10 cm; Longitudinal: 50 cm) ※Depends on footage location	Unknown (Depends on commercialization level and development accuracy)
Recording frequency Frame per second (fps) or Hz		Total: 10 fps Image: 30 fps LiDAR: 10 Hz IMU: 10 Hz MOBEYE : 10.64-10.87 fps	30 or 60 fps	Total: 10 fps Image: 30 fps IMU: 10 Hz MOBEYE: 12.5-16.67 fps
Measurement data	Subject Vehicle Position	GNSS/IMU	Camera (4K)	GNSS/IMU
	Distance between vehicles	From Lidar data (point cloud data)	Camera (4K)	From mobileye data
	Surrounding Vehicle Acceleration	From Lidar data (point cloud data)	Camera (4K)	Mobileye
	Surrounding Vehicles Position	Autoware (Mobileye)	Camera (4K)	Mobileye
	Road information	- Road shape and lane marking condition - Pseudo-curvature - Subject vehicle's distance to the lane marking	- Road shape and lane marking condition - Curvature, gradient (longitudinal section and transverse direction - Each vehicle's distance to the lane marking	- Pseudo-curvature - Subject vehicle's distance to the lane marking
	measurement range	- 70 m in front and behind of subject vehicle - 50 m on either side of the subject vehicle ※The range depends on the weather condition	150-350 m of the road section	-70 m in front and behind of subject vehicle ※Sensor range unknown on either side of the subject vehicle

The parameters used to define the extracted deceleration logical scenarios are the initial longitudinal velocity (Ve0) of the subject, the decelerating vehicle's longitudinal velocity (Vo0), the relative velocity (Ve0 - Vo0), the initial longitudinal distance between vehicles (dx0), and the maximum deceleration rate (Gx_max), as listed in Table 2. The parameters considered the initial value when a deceleration maneuver started except for the Gx_max, in which the maximum value was considered.

C. SCENARIOS EXTRACTION

Cut-in and deceleration logical scenarios were extracted based on specific parameter range values used to define both scenarios (See Table 3). While the duration of the cut-in scenarios was between two and 16 s, the duration of deceleration scenarios was larger than zero s and lower than 120 s. During the duration of each scenario, the subject vehicle was traveling straight forward without changing lanes or accelerating when it encountered a cut-in or a decelerating

TABLE 2. Parameters, notation, units, and types of value used to define cut-in and deceleration scenarios.

Parameters	Notations	Unit	Cut-in	Deceleration
Subject vehicle longitudinal velocity	Ve0	km/h	Initial Value	Initial Value
Challenging-vehicle longitudinal velocity	Vo0	km/h	Initial Value	Initial Value
Relative longitudinal velocity	Ve0-Vo0	m/s	Initial Value	Initial Value
Relative longitudinal distance	dx0	m	Initial Value	Initial Value
Relative lateral distance	dy0	m	Initial Value	—
Challenging vehicle lateral velocity	Vy	m/s	Maximum value	—
Deceleration rate	Gx_max	m/s^2	—	Maximum value

vehicle. Longitudinal distances between vehicles considered were set to positive values equal to or lower than 100 m in consideration of sensor ranges and safety metrics [48]. The considered lateral speed of the cut-in vehicle was set to positive values equal or lower than 5 m/s, considering road-to-tire grip limits in lateral motion [49].

Unlike functional scenarios that are usually theoretically described abstractly and linguistically [50], logical scenarios are described with kinematic and environmental parameters [51]. Although all parameters that describe the logical scenario are required, road geometry and weather parameters were eliminated to reduce the influencing parameters. For example, to avoid the influence of a road's curvatures on the vehicles' lateral velocity when traveling straight forward, the extracted scenarios were limited to highway sections with a road curvature of 0.0002 (1/m) or less. The consideration of scenarios that occurred on curved road sections requires more complex data processing approaches that combine the relative vehicle behaviors with road geometry. A second reason is to reduce the difference between interstate highways (more straight sections and less curved sections) and intra-city highways (fewer straight sections and more curved sections) in terms of the intended traveling speed and driving behavior. In the same context, the potential impact of weather on traffic intensity, demand, and safety [52], [53] and driving behavior [54] have also been excluded. Thus, this study only describes cut-in and deceleration logical scenarios with vehicle kinematic parameters.

The cut-in scenarios were extracted under the conditions that the longitudinal speed of the subject vehicle is higher than the challenging vehicle's longitudinal speed. The longitudinal distance between them is between 0 and 100 m. The maneuver starts when the lateral speed of the challenging vehicle increases from zero and ends when the lateral speed returns to zero, with the challenging vehicle driving straight forward in front of the subject vehicle. In the absence of other vehicles between them, the lateral velocity of a challenging vehicle remains constant in the same direction as the subject vehicle once it enters the lane of the subject vehicle from an adjacent lane, as shown in Figure 3. These conditions may contribute to limit the number of the extracted cut-in scenarios.

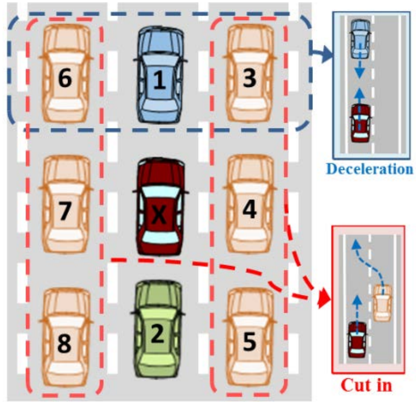

FIGURE 3. Extraction of cut-in and deceleration scenarios considering vehicle-to-vehicle interaction on highways. Vehicles identified with X, 1, and 2 refer to the subject, leading, and following vehicles, respectively. Other numbers refer to surrounding vehicles in the adjacent lanes. For source-1 and source-3, X can be the instrumented vehicle or a vehicle in the adjacent lane recorded by the instrumented vehicle that meets the extraction conditions. For source-2, X can be any vehicle that meets the extraction conditions within the recording range.

Consideration of a deceleration scenario was made when a vehicle's headway distance was reduced due to a preceding vehicle's deceleration instead of the acceleration of the following vehicle, as shown in Figure 3. Decreasing the challenging vehicle's longitudinal velocity reduces the longitudinal distance to the following subject vehicle in the absence of any vehicle between both vehicles. The maneuver starts when a challenging vehicle's longitudinal velocity starts decreasing (the acceleration rate increases in minus), and the subject vehicle synchronizes its speed accordingly. The maneuver ends when the longitudinal velocity stops decreasing, and the acceleration rate value returns to zero. Note that the initial longitudinal velocity of the decelerating vehicle could be lower/greater than or equal to the initial longitudinal speed of the subject vehicle so that the relative longitudinal distance may decrease/increase or remain unchanged during the maneuver.

D. PARAMETER DISTRIBUTIONS AND CORRELATIONS

First, the characteristics of each parameter range were analyzed, showing the distribution of each scenario parameter range to investigate the general driving behavior and quantify the parameter ranges. The distribution of each parameter is estimated numerically and iteratively by optimizing (i.e., minimizing) the least squared error between measured data and the estimated beta distribution. Here, the out-of-measurement range is excluded from the least squared

TABLE 3. Scenarios extraction conditions and scenario start and end values.

Scenario	Extraction condition	Start/end Value
Cut-in	-The cut-in vehicle's lateral velocity remains constant in the same direction. -The cut-in vehicle enters the subject vehicle's lane from an adjacent lane in the absence of other vehicles between them.	Start: the cut-in vehicle's lateral velocity increases from 0 m/s (Positive value to the right of the subject vehicle) End: the cut-in vehicle's lateral velocity returns to 0 m/s
Deceleration	-The decelerator vehicle's acceleration is a continuous negative value. -The decelerator vehicle is in front of the subject vehicle on the same lane in the absence of other vehicles between them.	Start: the decelerator vehicle's acceleration decreases from 0 m/s^2 (starts to take a negative value) End: the decelerator vehicle's acceleration returns to 0 m/s^2

error calculation. It enables estimation of the occurrence frequency beyond measurement range (i.e., extrapolation). This approach may cover both sensor range limitation and extreme edge cases of parameters. Scenario criticality was also evaluated using safety indicators and metrics, such as time to collision (TTC). Second, the correlations between parameter ranges were analyzed to evaluate the impact of each parameter on the challenging vehicle behavior during the maneuver. Correlations between every two parameters were determined using a two-dimensional distribution map for all parameters. Each parameter range in the X-axis is examined for all parameter ranges in the Y-axis, as detailed in Appendix B in the supplementary material.

E. PARAMETER RANGE EXTRAPOLATION

Traffic conditions broadly vary with time [32]. Hypothetically, a large amount of actual traffic data from multiple sources within a specific timeframe may not ensure that undetected cases during the observation time window do not indicate that they may not occur afterward. This reasoning raises the need for a methodology that assumes that events outside the observed parameter ranges may occur and can be defined to set the parameter ranges. Conversely, if limits of parameter ranges are not set or overextended, unrealistic events may occur. Therefore, parameter ranges must define dynamically possible traffic characteristics.

A possible method to reduce the possibility of edge cases outside the actual parameter ranges and data collection bias is to calculate the frequency of occurrence of each parameter, quantitatively set it within a specific confidence interval of that distribution, and extrapolate the interval based on the fitted distributions. Data extrapolation incorporates a specific range of extreme parameter ranges that the real-world traffic data measurements could not observe. Therefore, data distribution techniques are applied to fit the limited data distribution, and extrapolation techniques are applied to ranges outside the collected (Figure 4).

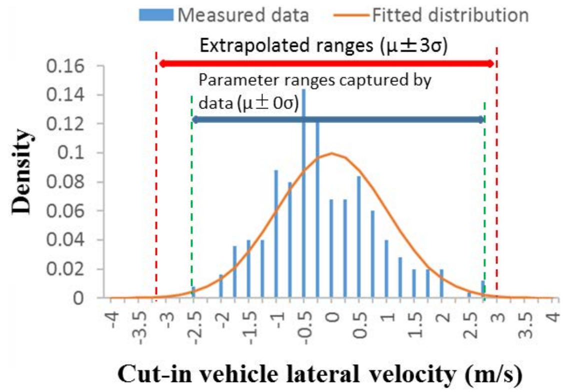

FIGURE 4. Example of parameter range extrapolation to non-measured events. See Appendix B in the supplementary material for more details on the extrapolation of all parameter ranges.

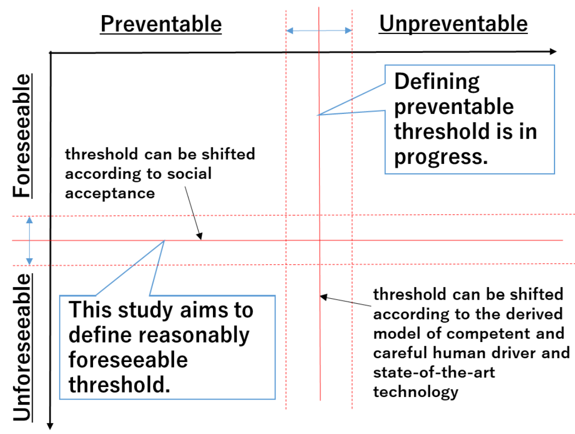

FIGURE 5. Model of reasonably foreseeable and preventable thresholds.

F. DERIVATION OF REASONABLY FORESEEABLE PARAMETER RANGES

Scenario-based testing that accounts for reasonably foreseeable parameter ranges can avoid rare and hypothetical cases or extreme vehicle behaviors unlikely to be relevant within the ADS capabilities in its operational domain. Scenarios with reasonably foreseeable parameters are viewed as extensions of forecastable events that are more likely to occur within a specific ODD and period. These are considered the upper and lower limit of the parameter range, influenced by the variation of social acceptance and the minimum risk acceptance between countries, as shown in Figure 5. Although rare cases can be excluded, quantitative thresholds cannot be defined because social acceptance levels may differ among domains and regions.

Based on models that account for the behavior of the surrounding traffic into ADS, the assessment should cover adequate functional scenarios that can thoroughly assess the long-term effect of ADS behavior on the environment and all road users. The selection of functional scenarios should have robustness and constancy, considering the number of modeling parameters required to describe the logical

TABLE 4. Breakdown of cut-in and deceleration scenarios according to data source and vehicle speed ranges.

Scenarios	Veo (km)	Datasets			Total
		source-1	source-2	source-3	
Cut-in	< 60	28	25	4	57
	≥ 60	55	147	701	903
Deceleration	< 60	862	0	0	862
	≥ 60	5,880	0	0	5,880

scenarios to avoid excessive scenario complexity and build-up of the interacting parameters. Based on the definition of logical scenario and the distribution of parameter ranges, the surrounding traffic behavior can be considered within the reasonably foreseeable parameter ranges. Technically, cumulative probability from the most frequent combination is calculated numerically and added up to the threshold. At the same time, it is difficult to determine the rare combinations of multi-dimensional parameters theoretically. Parameter combinations within the threshold are considered reasonably foreseeable.

III. RESULTS

Table 4 provides an overview of the extracted cut-in and deceleration scenarios from each data source. The cut-in scenarios were extracted from all three sources, whereas the deceleration scenarios were extracted solely from source-1. The measurement vehicles of source-1 are equipped with Lidar sensors with higher abilities to accurately detect distant start points of decelerating vehicles compared to the over-highway fixed camera of source-2 and the measurement vehicles of source-3. However, since a cut-in maneuver was only selected when the cut-in vehicle's initial velocity was lower than the subject vehicle's velocity (Ve0 - Vo0 > 0), the cut-in scenarios sample size was significantly smaller than that of the deceleration scenarios. For the deceleration scenario, although only expert drivers drove the instrumented vehicles, data from random drivers have also been included because the instrumented vehicles could also capture deceleration events against vehicles in the adjacent lanes.

The traffic data were first collected at all speed ranges (Ve0 > 0 km/h). Hence, Japan expressways from which the data were collected are designed to accommodate motor vehicles circulating at high speeds [44], [45]. Therefore, the collected data were divided into low and high-speed range categories based on the subject vehicle's velocity (Ve0) at which the cut-in and deceleration maneuvers occurred. It is apparent from Table 3 that very few maneuvers occurred at speed ranges lower than 60 km/h compared with speed ranges equal to or greater than 60 km/h. The lower-speed traffic data were collected during unusual conditions, such as dense traffic during rush hours, traffic jams due to traffic crashes, and near tollgates [55]–[57]. To analyze and understand lower-speed traffic data requires considering external parameters of traffic and road conditions. Furthermore, research into the car-following behavior in expressways observed a significant difference in driving behavior between the low and high-speed ranges [58]. This study considered scenarios when maneuvers occurred at speed ranges equal to or greater than 60 km/h.

In the first subsection, the distributions of parameter ranges have been calculated and analyzed, clarifying the density of each parameter to quantify the frequency of the cut-in and deceleration parameter ranges. This process is necessary to determine the risk exposure and incorporate the results with the annual risk acceptance to define reasonably foreseeable parameter ranges.

A. DISTRIBUTION OF PARAMETER RANGES

1) LANE-KEEP CUT-IN

Figure 6 shows the distribution of each parameter range of cut-in scenarios. The sensors and cameras scanned lanes for vehicles up to 70 m in front of the subject vehicle while driving at velocities equal to or higher than 60 km/h. The results show that the cut-in maneuvers occurred at subject vehicle velocities ranging from 60 to 137.9 km/h and at cut-in vehicle velocities ranging from 43 to 128 km/h. The relative longitudinal velocity and distance ranged from 0.01 to 50 km/h and 8 to 70 m, respectively.

The initial longitudinal velocity results of the subject vehicle(Figure 6: top-left) show that increasing the driving speed leads to an increase in the density of cut-in maneuvers up to speed ranges between 100 and 110 km/h; from thereon, the density decreases as the speed increases beyond 110 km/h. There could be two explanations for such driving behaviors. One is related to the impact of traffic rules and the maximum speed limit on the frequency of cut-in scenario occurrence at a high driving speed range. The other is related to the influence of the surrounding driving behavior on the individual driving speed. Traffic rules and the surrounding environmental factors might affect the density of cut-in scenario maneuvers at speeds greater than 110 km/h. Such effects are expected and should be considered when the data is collected within a specific time. Hence, an extrapolation from observations of limited duration has been applied.

The relative longitudinal velocity results (Figure 6: top-right) depict that the tendency of drivers to perform cut-in maneuvers increases when the relative velocity decreases. Considering the scenario extraction condition that the subject vehicle velocity must be higher than that of the cut-in vehicle, the drivers tend to cut in front of faster vehicles more often when the speed difference is less than 10 km/h. Although some drivers cut in front of a faster vehicle with a speed difference of more than 50 km/h, the relative distance was significant, and the drivers might judge that it is safe to change lanes [59].

Figure 6: bottom-left shows that the number of cut-in maneuvers increases as the relative longitudinal distance increases. The shortest longitudinal distance between vehicles was 8.3 m and is associated with the smallest number of cut-in scenarios. The largest longitudinal relative distance

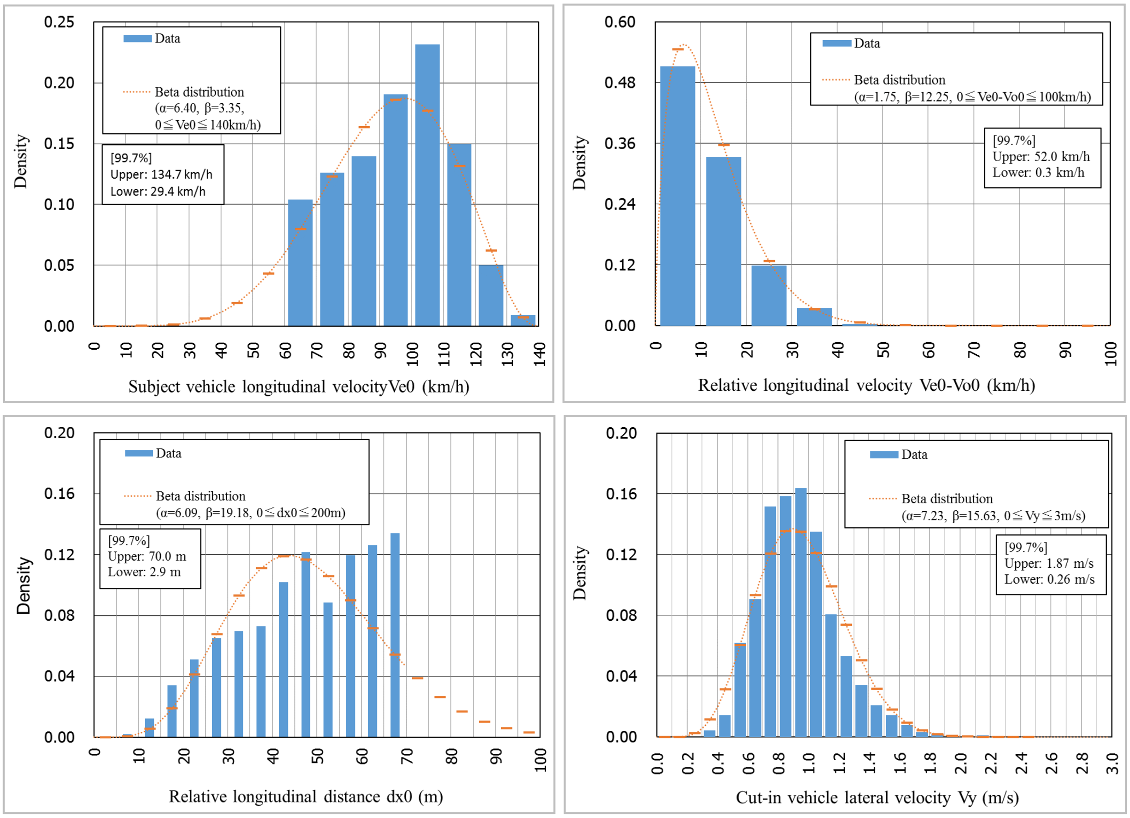

FIGURE 6. Cut-in scenarios: Distribution of parameter ranges showing the density of each parameter. The regression line of distribution parameters α and β is estimated with each class. The approximated α and β are obtained as a function of two parameters. Distribution is re-calculated with the approximated α and β.

was approximately 69 m and is associated with the most significant number of cut-in scenarios. Lane-change crash statistics reveal that the most common crashes are likely to occur in the range from 1.2 m in front of the cut-in vehicle to approximately 9 m behind the cut-in vehicle [60]. Therefore, it can be inferred that most drivers tend to maintain a safe longitudinal distance during cut-in maneuvers.

The cut-in lateral velocities (Figure 6: bottom-right) ranged between 0.2 and 2 m/s, which can be judged as a smooth lane change maneuver [61]. The peak value of the lateral velocity is around 1 m/s. Comparing the results of lateral velocity with the longitudinal velocity of the cut-in vehicle indicates that the lateral acceleration rate of the vehicle reduces at higher speeds more than 100 km/h and reaches the peak value at speeds from 70 to 100 km/h. In consideration of the cut-in direction, there were 818 maneuvers from the left of the subject vehicle and 167 maneuvers from the right of the subject vehicle. The most significant Vy0 values were 3.15 m/s and 2 m/s for cut-in maneuvers from the right and left, respectively. Noting that the largest Vy0 values were not associated with higher vehicle speeds, it would be better to investigate safety indicators that incorporate the relation between parameters, such as the TTC. The TTC between vehicles has been considered to distinguish between critical and normal driving behavior between vehicles. It can be a measure for rating the severity of traffic conflicts and a cue for decision-making in traffic. This study calculates the TTC value as the relative longitudinal distance between vehicles divided by the relative longitudinal velocity.

Analyses were conducted for the relative velocity and distance in TTC to further understand the management of the rearward distance of the driver during cut-in maneuvers. The shortest TTC value was 3 s as reached while the velocity of the subject vehicle was 97 km/h, the relative longitudinal distance was 18.8 m, and the relative velocity was 16 m/s. The TTC values indicate that as the relative velocity increases, the relative distance also increases such that the TTC value remains within a relatively safe range. TTC values appear to depend on the speed and relative distance of the vehicle, and there was no critical cut-in maneuver detected with the recorded speed range. It appears that only 1 % of drivers performed the cut-in maneuver with a TTC value of less than 5 s. Approximately 83 % of the drivers preferred a distance of more than 30 m rearward, a relative velocity of less than 30 km/s, and a TTC of more than 7.5 s for the subject vehicle to initiate a cut-in maneuver. The overall cut-in data set analysis revealed that the vast majority of the extracted scenarios were neither high in urgency nor severity.

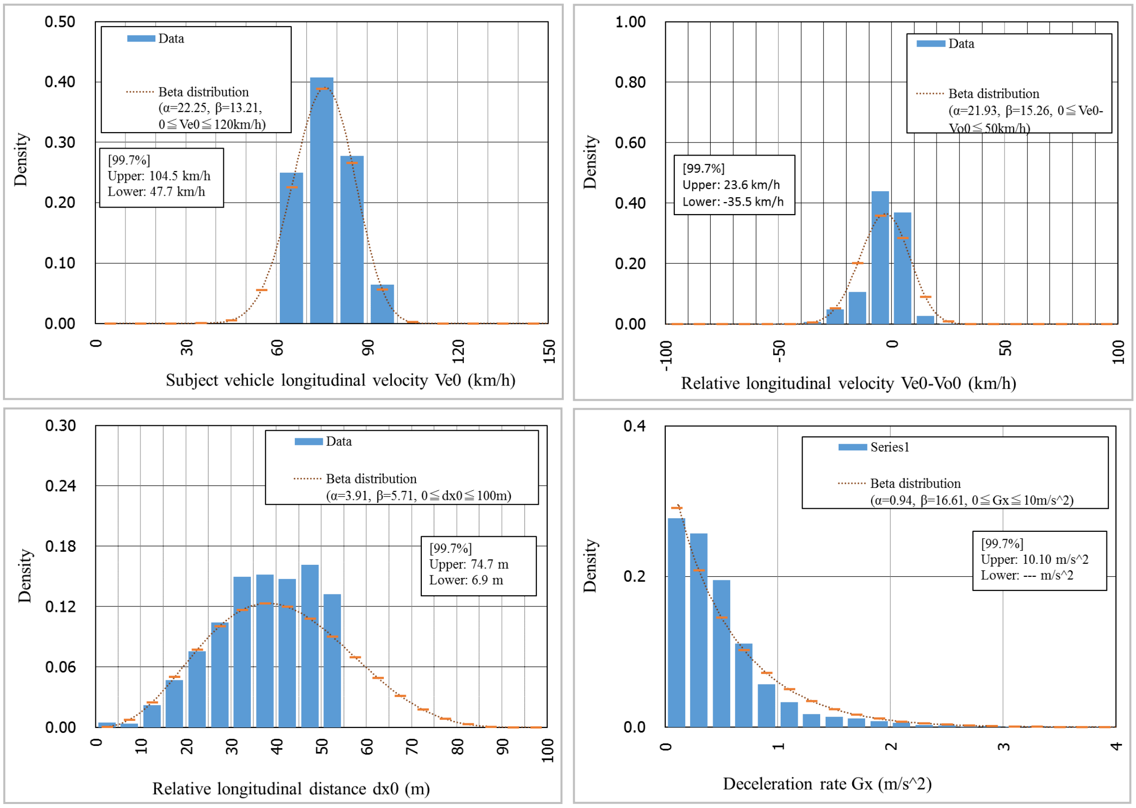

FIGURE 7. Deceleration scenarios: Distribution of parameter ranges showing the density occurrence of each parameter. The approximated α and β are obtained as a function of two parameters. Distribution is re-calculated with the approximated α and β.

2) LANE-KEEP DECELERATION

Figure 7 shows the distribution of the four parameters used to define the logical deceleration scenarios. The overall analysis revealed that all deceleration maneuvers occurred at a speed slower than 104 km/h. Results of the subject vehicle's initial longitudinal velocity (Figure 7: top-left) revealed that 40% of the deceleration events occurred at speed ranges between 70 and 80 km/h. Considering the speed limit and the velocity of the subject vehicle during the deceleration scenarios may indicate that the deceleration events occurred in denser traffic. However, the type of highway (e.g., inter-state versus intra-state) may also influence driving behavior in longitudinal vehicle control. The maximum density (75%) of the maneuvers occurred when the initial relative longitudinal distance (Figure 7: top-right) ranges between 30 and 50 m (time headway > 2 s), which can also be regarded as not highly critical situations.

The largest value of the maximum deceleration rate (Figure 7: bottom-right) was 4 m/s^2 when the subject vehicle velocity was approximately 75 km/h, and the relative distance (Figure 7: bottom-left) was less than 50 m. The smallest value of the maximum deceleration rate was 0.0001 m/s^2 when the subject vehicle speed was less than 70 km/h, and the relative distance was less than 30 m. Although the subject vehicle speed was above 60 km/h for the selected maneuvers, the deceleration rate values are below 2.5 m/s^2, which are within the comfortable range [62]. A general statistical inspection of the data set may conclude that the maximum deceleration rate depends not on the speed range or relative distance. However, the driver's deceleration frequency may increase as the vehicle velocity decreases.

Further inspection with the TTC parameter between the subject and decelerating vehicle revealed that the shortest TTC was 2.5 s as reached when the subject vehicle's velocity was 68 km/h, the relative velocity was 7.6 km/h, and the relative distance was 5.2 m. Although a decelerating maneuver with TTC less than 3 s can be highly critical and likely to result in rear-end collision, the deceleration rate is very low, 0.005 m/s^2. In total, approximately 99% of the deceleration maneuvers occurred at TTC values more than 6 s with a relatively low Gx-max value, which revealed that these maneuvers were also uneventful. In conclusion, the drivers tend to maintain a safer distance to the vehicle in front to have enough time to react. Thus far, these results may not be enough to highlight the impact of each parameter on the management of the driver of other parameters. The following section investigates the correlation between parameters, highlighting the influence of each parameter in terms of safety envelope.

B. PARAMETER RANGE CORRELATIONS

Regression analysis was used to predict the correlation between parameter ranges. A linear regression model uses one parameter range as an explanatory variable in the X-axis.

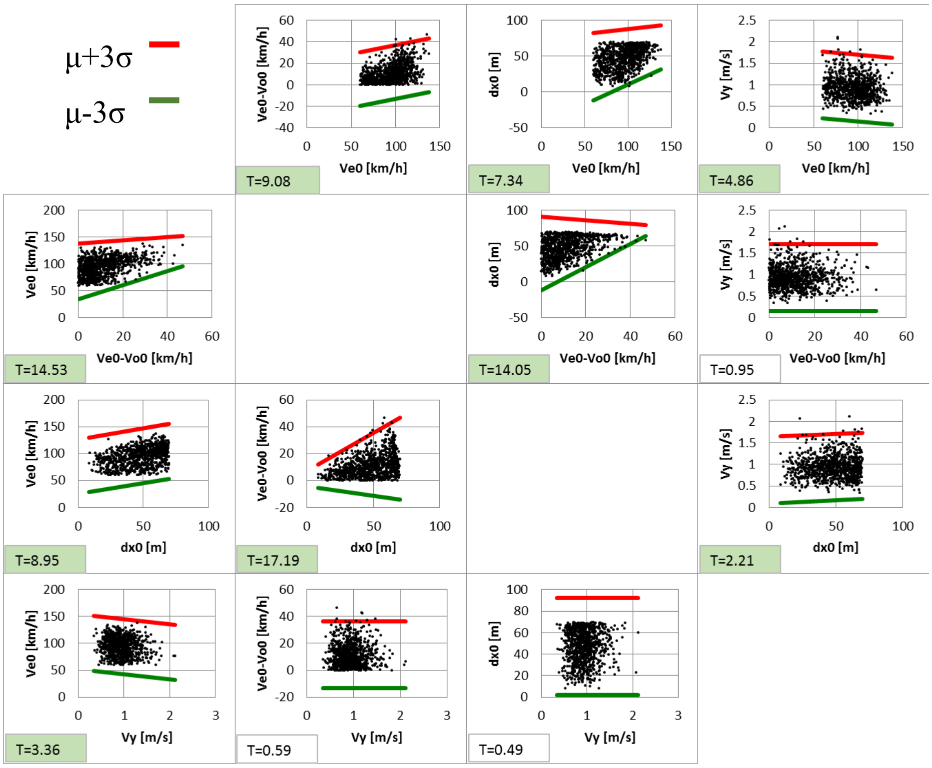

FIGURE 8. Cut-in scenario: Cross correlations between parameter ranges (Ve0; Ve-Vo0; Vy; dx0). T: t value ($t \geq 1.96$ is highlighted). See Appendix B in the supplementary material for more details on ($\mu \pm 3\sigma$) calculations.

The mean and standard deviation of the other parameter ranges as objective variables in the Y-axis are applied to all parameter ranges separately for each type of scenario. The same analysis is also performed by reversing the relationship between the two parameters. The slope and intercept values are illustrated in the figures for each correlation. T-tests were used to analyze the significance of the relationship. Based on the regression analysis results, it is evaluated whether every two parameters correlate based on the superiority of the slope value (when $t \geq 1.96$). If the slope is superior, the mean or standard deviation of the parameter-Y will change with (the class value of) the parameter-X; therefore, it is determined that correlation must be considered.

1) LANE-KEEP CUT-IN

The correlation analysis between the parameter ranges of the cut-in scenario in scatter plots is in Figure 8. The analysis indicated significant correlations between Ve0 and Ve0-Vo0, dx0, and Vy such that the relative velocity and distance tend to increase, and the lateral velocity decreases as the subject vehicle's velocity increases. These relationships may be explained by considering safe driving behaviors to maintain larger time headway between vehicles at higher speed ranges. In line with previous studies and consideration of vehicle dynamics, it is evident that the head angle of the cut-in vehicle decreases when it performs lateral maneuvers at higher speed ranges [63]. This maneuver is to maintain a balance between vehicle speed, yaw, roll, and pitch angles. However, the correlation results between Ve0 and Vy are contradictory to previous findings by Thal (2020), in which there was no correlation observed. While Thal (2020) considered all speed ranges of the subject vehicle, only high-speed ranges ($Ve0 \geq 60$) are considered in this study. It can, therefore, be concluded that the correlation between Ve0 and Vy is sensitive to the range of Ve0.

The second row of Figure 8 highlights significant correlations between Ve0-Vo0 and Ve0 and dx0. Both the velocity of the subject vehicle and relative longitudinal distance increase when the difference between the subject vehicle and the velocity of the cut-in vehicles increases. However, Ve0-Vo0 and Vy are not correlated. These results indicate that the lateral velocity is dependent on the speed of the vehicle and is not influenced by the behaviors of the other vehicle.

The third row in Figure 8 shows significant correlations between dx0 and Ve0, Veo-Vo0, and Vy. The apparent associated trend of increase in the velocity of the subject vehicle and relative velocities with the increase in dx0 further confirms the strong correlation between Ve0, Ve0-Vo0, and dx0 as well as its dependency dx0 on the changes in Ve0 and Ve0-Vo0 values. Although the analysis indicates that Vy is affected by the increase in dx0, this correlation is weak and could result from the indirect effect of the vehicle speed. Comparing Vy data from the third row with the data from the first and fourth rows in Figure 8 shows that the Vy is

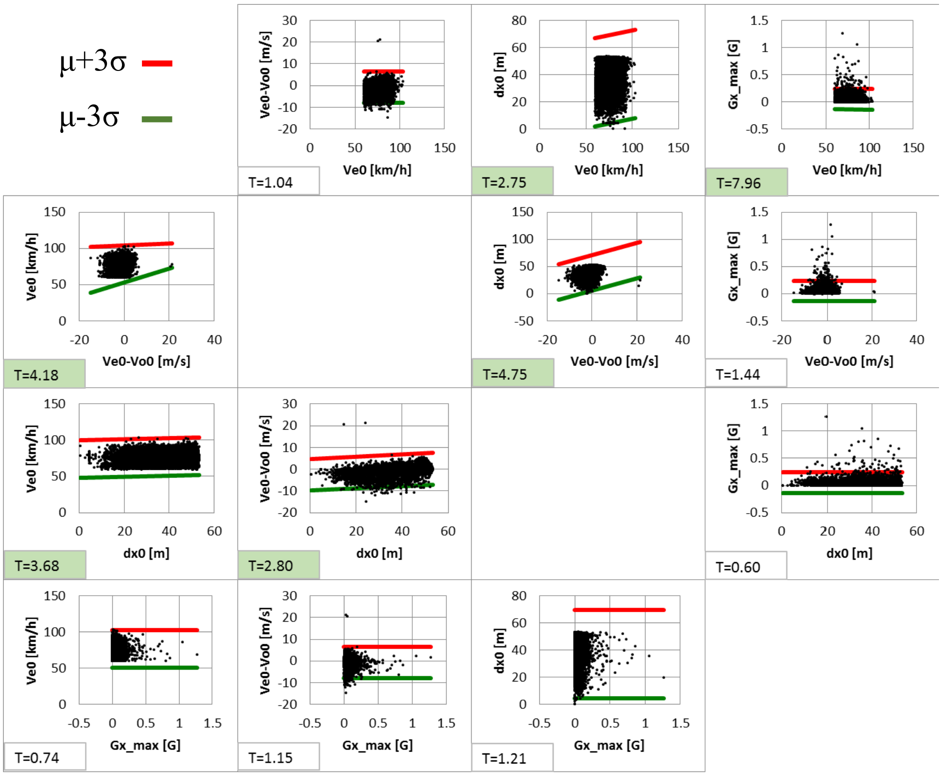

FIGURE 9. Deceleration scenario: Cross correlations between parameter ranges (Ve0; Ve-Vo0; dx0; Gx_max).

negatively correlated with Ve0, but it does not correlate with dx0 or other variables.

Overall, the analysis of parameter correlations for the logical cut-in scenarios indicates strong correlations amongst the interacting parameters. The analysis also highlights that while some parameters are dependent on the potential conflict with the surrounding traffic (e.g., Ve0-Vo0 and dx0), other parameters, such as the lateral velocity, depend more on driving behavior and safety and are less affected by the other road users.

2) LANE-KEEP DECELERATION

The results obtained from the correlational analysis of the deceleration scenarios parameter ranges are presented in Figure 9. For the Ve0, the analysis highlights significant correlations with dx0 and Gx_max. The relative longitudinal distance increases with subject vehicle velocity, which is explained by the driving behavior and the tendencies of the driver to maintain safe time headway between vehicles. Although the analysis indicates that Ve0 and Gx_max are correlated with consideration to the mean values (T $(\mu) =$ 7.96), further statistical tests, which consider the slope and intercept, revealed a weak correlation (T $(\sigma$ slop$) = 1.87$; T $(\sigma$ intercept$) = 4.03$). Together and compared to Gx_max data, the analysis of the fourth row in Figure 9 concludes that the deceleration rate is an independent variable and is more related to the decisions of the driver in consideration to the front traffic as opposed to the following traffic.

Correlations were found between Ve0-Vo0 and Ve0 and dx0, but not between Ve0-Vo0 and Gx_max. On average, Ve0 and dx0 showed a clear increase associated with the Ve0-Vo0 increase. This correlation is dependent on the driving behavior of the drivers of the subject vehicle in terms of vehicle speed harmonization and safety in consideration of the decelerating behavior of the vehicle [64]. This conclusion is also supported by the significant correlations in the third row of Figure 9. From the fourth row in Figure 9, no significant increase or decrease in Gx_max can be seen.

In summary, these results show that the cut-in scenario parameters are more correlated than the deceleration scenario parameters. A vehicle is entering the driving course of another vehicle in the cut-in scenario; therefore, both vehicles must harmonize their speed and relative distances. The drivers of the challenging vehicle usually plan and respond according to the traffic ahead for the decelerating scenarios. In contrast, the drivers of the following vehicle must harmonize with the preceding decelerating vehicle [65].

C. OCCURRENCE FREQUENCY OF PARAMETER RANGES

The occurrence frequency of an arbitrary parameter combination can be derived based on the results of the correlational analysis and causal relation of parameters. For example, the occurrence frequency derivation of cut-in scenarios can be summarized as follows. First, the initial relative speed and distance frequency are calculated with an arbitrary subject

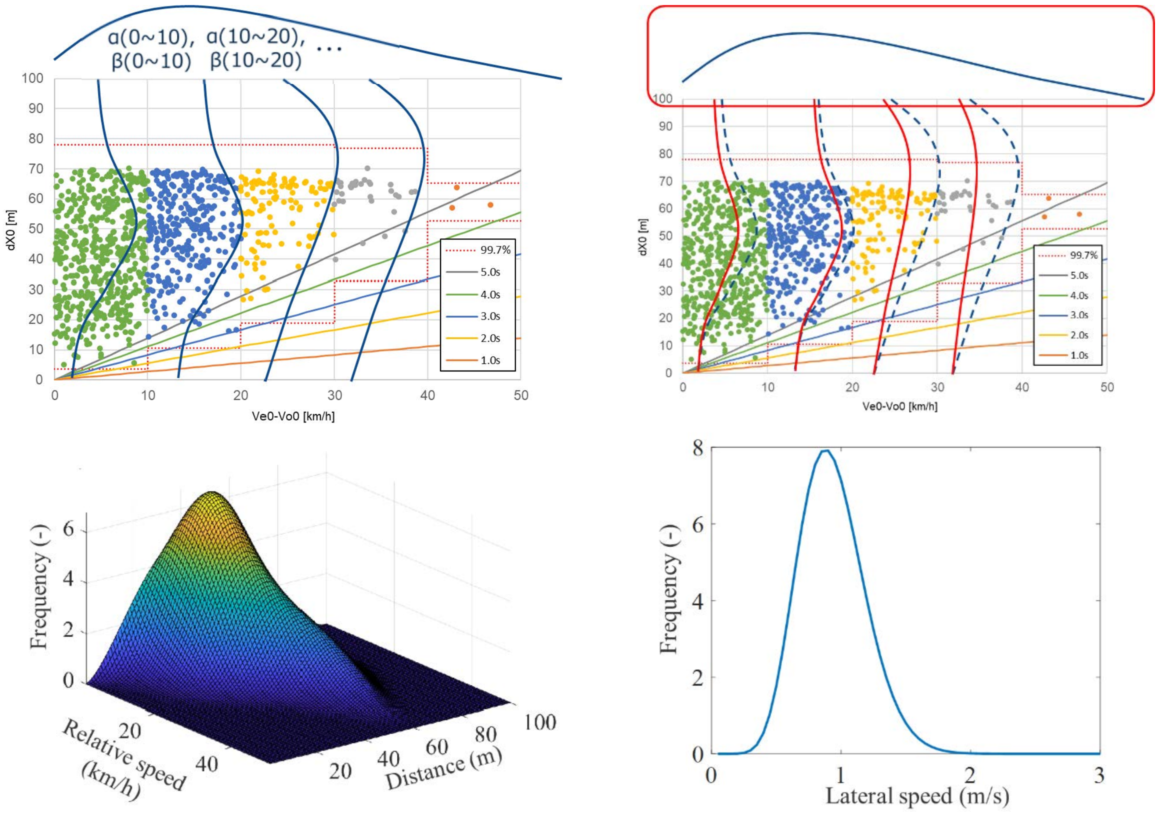

FIGURE 10. Occurrence frequency p1 and p2 of cut-in scenarios. The top-left graph represents the estimated α and β distribution by classes to estimate continuous α(Vrel), β(Vrel) by discrete α_n, β_n. The top-right graph estimates the weight function from the distribution of Vrel. The bottom-left graph represents the combined occurrence frequency of relative speed and longitudinal distance to calculate multi-dimensional distribution (Input: α(Vrel), β(Vrel), and weight function; Discretization: Frequency to probability). The bottom-right graph represents the frequency of the lateral speed.

vehicle speed, Ve0. Second, the correlated frequency of the initial relative speed and distance is defined as p_1(Vrel, dx) depending on Ve0, as shown in Figure 10 top. Third, the maximum lateral speed frequency is defined as p_2(Vy) depending on Ve0, as shown in Figure 10 bottom. The occurrence frequency of the cut-in parameter combination is determined as $P_{cut-in} = p_1 \times p_2$. Here, p_1 and p_2 represent the combined frequency of the initial relative speed and distance and the frequency of the maximum lateral speed under a specific range of Ve0, respectively.

Similarly, the occurrence frequency of deceleration scenarios can be summarized through the calculation of the initial relative speed and distance frequency with the assumption of an arbitrary speed of the subject vehicle Ve0. With the correlated frequency being contingent to the Ve0, the initial relative speed and distance are defined as p_3(Vrel, dx), whereas the frequency of the maximum deceleration is defined as p_4(Gx). The occurrence frequency, represented by the deceleration parameter combination, is defined as $P_{dec} = p_3 \times p_4$. Here, p_3 and p_4 represent the combined frequency of the initial relative speed and distance under a specific range of Ve0 and the frequency of the maximum deceleration rate, respectively.

IV. DISCUSSIONS

This study was designed to contribute to the development of socially acceptable safety assurance methodologies to test automated driving vehicles. The first aim was to propose a method that incorporates real-world traffic monitoring data into the definition of reasonably foreseeable parameter ranges for AV test scenario generation. The Scenario-based approach is the main focus of the proposed method to assess the safety of the intended functionality. This method presented sequential steps to identify the most relevant AV safety assessment scenarios. Since this is a great challenge and an important issue for future research and road traffic safety, this study provided detailed information to enable method replication in different countries and environments, disregarding the data collection sources and types of scenarios.

This study set out with the second aim of applying the method to define parameter ranges for cut-in and deceleration scenarios based on a set of traffic data collected on Japanese highways for the current purpose. The data set comprised three different sources acquired with both instrumented vehicles and fixed cameras over road sectors between 2017 and 2020. The algorithms detected 903 cut-in and 5,880 deceleration maneuvers observed. Each scenario was defined with kinematic parameter ranges, such as longitudinal and lateral velocities, relative velocities and distance, and deceleration rate. The data analysis resulted in interesting findings regarding the distribution of parameter ranges, maneuver frequency, and parameters correlation.

The entire data set analysis revealed no crash occurrences for both scenarios, and the vast majority of the maneuvers were neither high in urgency nor high in severity. Given that lane change crashes are rare events on Japanese highways [66] and lane change crashes are a relatively small subset of all crashes [61], not observing a crash during the data collection period is reasonable for the cut-in scenarios. It is somewhat surprising that no crash was noted in the deceleration data.

To what extent does the collected data correspond to the general real-traffic driving behavior is influenced by several humans, vehicular, and environmental factors. Moreover, the road type and structure may also influence the driving behavior and driver's safety management, notably in the scenarios where the subject vehicle is the instrumented vehicle driven by expert drivers who are aware that their driving behavior was monitored and later investigated. Research has also observed differences between professional and non-professional drivers' reaction time and safety management [52]. Furthermore, the extracted scenarios involved cars and did not include trucks, buses, and motorcycles. The distribution of parameter rages was extrapolated to cover some rare and unusual events to reduce the effect of such influential factors.

Correlations among parameters were investigated to understand driving behavior and highlight parameters with a significant effect on the frequency of each scenario. The analysis indicated that the cut-in scenario parameters are more correlated than the deceleration scenarios' parameters because cut-in drivers have to monitor objects in the adjacent lane behind their vehicles before cut-in initiation. Therefore, the cut-in drivers make decisions and synchronize their speed based on the traffic stream in the adjacent lane. For the deceleration scenario, the decelerating drivers make their decisions either in response to the front vehicle driving behavior or on their own with no or limited consideration of the rear vehicles. Caution should be taken as these findings are limited to straight road sections with limited access to highways and may not be generalized for other types of roadways.

An interesting finding is that the most correlated parameters are velocity and relative distance for both scenarios. When a vehicle's velocity is 60 km/h or greater, the results indicated that the frequency of cut-in scenarios increased at a speed range greater than 100 km/h. In contrast, the deceleration scenario frequency reached its maximum speed range between 75 and 85 km/h. However, the frequency increased as the relative longitudinal distance increased, and the relative velocity approached zero in both scenarios. These findings suggest that reasonably foreseeable parameter ranges may be inferred using the relative velocities and distance values.

The third aim of this study was to contextualize the proposed method and the resulting parameter ranges with risk acceptance thresholds that are considered acceptable in different international environments for quantification of "reasonably foreseeable" or "relevant exposure". According to the International Safety Standard ISO/IEC Guide 51, safety assessment methods must indicate the safety of autonomous driving systems by covering various situations deemed "reasonably foreseeable". In general, "reasonably foreseeable" relates to the frequency of specific risk encounters. However, possible hazard occurrence must be considered, regardless of infrequent encounters. For example, in Japan and the USA, the nuclear reactor-related acute mortality risk may not exceed 0.1% [67], [68]. In 2001, the Japanese mortality risk was 7.7×10^{-3}/year, with cancer accounting for 1/3 (2.4×10^{-3}/year). This rate refers to not exceeding a value of approximately 10^{-6}/year. Stringent railway risk assessment, with Japanese high-speed trains (Shinkansen) as the strictest, occurs at the design stage with accident probability occurrence 10^{-6} times/year [69].

The AV safety evaluation threshold value can be conceived with the predefined risk evaluation reference [70]. While nuclear power plant accident hazards are extensive and innumerable, car crash occurrences on highways are limited to the location and amount to lesser damage. Hence, the cut-in/deceleration parameter ranges are considered with the assumption that the annual individual encounter probability threshold value is 10^{-6}. The measurements for time, length, and cut-ins are currently measured in the Source-1 database.

Under the premise that most frequent professional drivers (such as highway bus drivers) perform an average of 8 hours a day, 240 days a year [71], these drivers encounter 3,867 cut-ins per year. The substitution in equations 1 and 2 excludes parameter ranges with an annual encounter probability of 10^{-6} or less. Probability P and Expectation E are arbitrary combinations of cut-ins below p percentile, which occur more than once in a year, can be derived as follows:

$$P = 1 - (1-p)^n \tag{1}$$

$$E = \sum_{k=1}^{n} (1-p)^{n-k} = np \tag{2}$$

Here, n is the number of cut-ins or decelerations per year.

To consider reasonably foreseeable parameter ranges, we converted the distributions provided in the previous section to annual occurrence probabilities with the equation. Based on occurrence frequency P_{cut-in} and P_{dec} described in the results section and conversion to an annual expected value, reasonably foreseeable parameter ranges can be expressed in Figure 11. The Green area represents that 99% of the cut in the parameter combination occurs within the range, the yellow area represents 99.7%, and the red area represents the $1-10^{-4}$ percentile (10^{-6} times per year). For example, the cut-in scenarios in the red area occur with a lateral speed of more than 2.6 m/s, a relative distance less

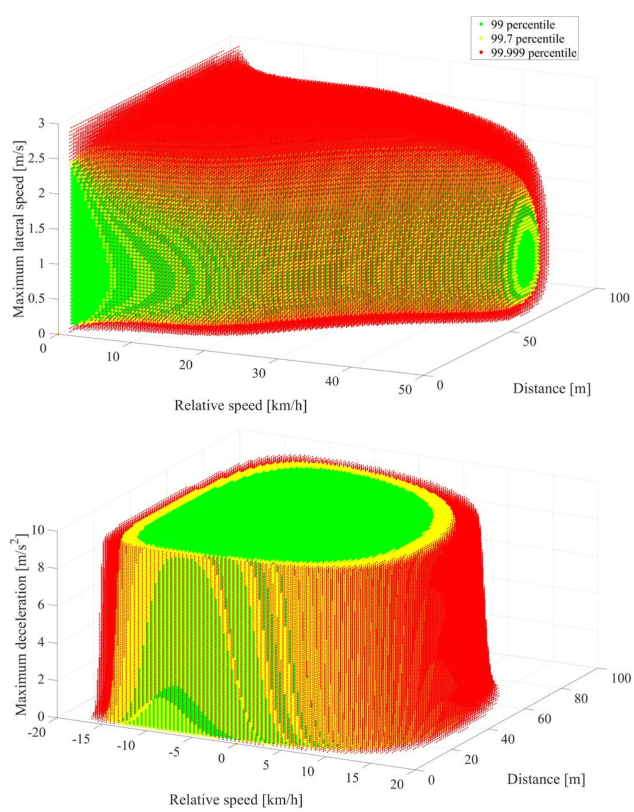

FIGURE 11. An example of reasonably foreseeable parameter ranges for cut-in (top) and deceleration (bottom) scenarios based on risk exposure that a driver may encounter on Japanese highways.

than 5 m, and a relative speed of more than 25 km/h, while in the orange area occur with a lateral speed more than 2.2 m/s, a relative distance closer than 20 m, and a relative speed more than 30 km/h.

Similarly, the drivers may encounter decelerations 5.62 times/h (10783 times/year). Hence, reasonably parameter ranges for both scenarios are defined with relevant exposure, as shown in Figure 11. It is noteworthy that encountering events refers to the exposure rate and not the risk value. Therefore, the defined range.

These results indicate that a driver on Japanese highways is likely to encounter a cut-in with a relative speed of 40 km/h from 30 m or closer less than 10^{-6} times per year. Similarly, a driver may encounter deceleration events with a relative speed of 20 km/h from 20 m or closer less than 10^{-6} times per year. Note that actual parameter ranges must be determined based on each country's social acceptance; the threshold can be varied by the assumption of driving hours and acceptable exposure.

V. CONCLUSION

This study proposed a method to parameterize scenarios extracted from real-world traffic monitoring data and later incorporated the results of parameters distribution and correlation into the definition of reasonably foreseeable parameter ranges. Focusing on the probability of hazards arising from the surrounding traffic's impact on AV performance and safety, we applied the proposed meth to define parameter ranges for cut-in and deceleration scenarios extracted from Japanese highways while providing detailed information to enable replication in other countries and environments. Using analytical tools, calculations for the minimum range of the most relevant parameter ranges, along with the assessment of the associated risk exposure for each type of logical scenario, were performed to define a finite number of reasonably foreseeable parameter ranges. In turn, this renders a wide range of test cases to be diminished and modeled to enable the AV safety assessment to be implemented with the most representative test cases exhibiting ADS behavior.

We contextualize the resulting parameter ranges with risk acceptance thresholds considered acceptable in different environments (i.e., railway transport) and domains (i.e., nuclear power plants) to identify the most representative test cases for scenario-based testing covering critical and non-critical situations. Defining reasonably foreseeable parameter ranges based on the risk acceptance and relevant exposure significantly limits the number of traffic situations required to ensure ADS safety. Such an approach will prove useful in expanding our understanding of scenario-based assessment conductions based on broader traffic situations and traffic data acquired from other countries.

Notwithstanding that, cross-international studies involving real-world traffic data are also needed to compare the findings. Real-world traffic datasets from different countries can be extracted, processed, and compared provided that a consistent methodology is applied. The scenario extraction and parameterization approach developed in this study can be applied to store the parameter set of each scenario as a concrete scenario to investigate similarities and correlations as well as differences across different datasets to find factors that can affect the safety assessment methodology in different countries. Conversely, with the spread of automated, autonomous, and connected vehicles, an iterative implementation of the proposed method shall update the test cases to incorporate the changes that may be induced by the vehicles in the real traffic.

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(H. Nakamura and H. Muslim are co-first authors.)

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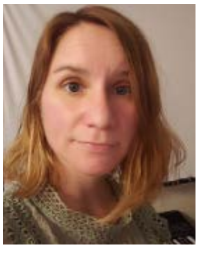

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