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Research Article

Applying the Operational Design Domain Concept to Vehicles Equipped with Advanced Driver Assistance Systems for Enhanced Safety

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Advanced driver assistance systems (ADASs) assist drivers by alerting them of the occurrence of events based on the sensing capabilities of the vehicle, reducing the effort required by drivers. Most vehicles that are recently launched vehicles have been endowed with ADAS, thereby significantly reducing traffic accidents. However, the Insurance Institute for Highway Safety has reported that traffic accidents caused by driver negligence may increase as drivers have become accustomed to using ADAS. Therefore, drivers must be provided with sufficient information on the appropriate use of ADAS through user manuals. In this study, the regulations regarding the presentation of the operational design domain (ODD) in ADAS user manuals were analyzed. The results indicated that most user manuals do not sufficiently specify the ODD, which is claimed important by various organizations for ensuring safe driving. Additionally, the expression of the limitations and performance of ADAS is ambiguous because most countries are not regulated to explicitly present the ODD when writing ADAS user manuals. Therefore, in this study, the ODD guidelines for presenting ADAS specific to vehicle manufacturers and governments have been outlined in addition to guidelines for drivers on using ADAS. These guidelines can contribute to the development of clear ADAS user manuals, which in turn can ensure the safe driving of ADAS-equipped vehicles.

1. Introduction

Advanced driver assistance system (ADAS) technology assists drivers with respect to lane keeping, vehicle speed management, and automated braking systems [1]. These systems are primarily designed to improve driver comfort and ensure safe driving through warnings and active intervention in situations that warrant the implementation of necessary actions [2]. The rapid development of ADAS has led to both luxury vehicles and low-end vehicles being equipped with ADAS functions, such as autonomous emergency braking (AEB) [3].

According to the Insurance Institute for Highway Safety, the traffic accident rate has decreased by 41% after the application of forward collision warning (FCW), a major safety function of the ADAS, to trucks [4]. However, traffic accidents may continue to occur owing to the negligence of drivers who are accustomed to using ADAS [4]. Therefore, Teoh [4] proposed a system that requires the active participation of drivers when using ADAS technology.

In 2020, the Korea Consumer Agency conducted a survey of 500 consumers driving vehicles that were launched after 2018. The survey results indicated that only 8.2% of the consumers were aware of the ADAS-related content in the user manuals and only 9.9% had read the manuals. Furthermore, more than 50% of the consumers indicated difficulty in obtaining useful information from the manuals because of their unsatisfactory portability and readability. Therefore, traffic accidents caused by the use of ADAS can be attributed to driver negligence. Moreover, the nonstandardization of ADAS manuals has been considered disadvantageous [1].

Automated vehicles (AVs) exhibit tremendous potential to increase road capacity, promote transport safety, and reduce fuel consumption [5]. Based on the rapid development of automated driving systems (ADSs), the Society of Automotive Engineers (SAE) International has defined ADS levels 0–5 in six stages [6]. For automated driving level 3 or higher, methods for systematically managing user manuals are globally under discussion. Furthermore, by clearly presenting the operational design domain (ODD) of AVs in user manuals, safe driving can be ensured by increasing the driver's understanding of AVs. However, quantitative and qualitative analyses of user manuals sold in Australia in 2018 indicated that ADAS functions corresponding to automated driving levels 1 and 2 of SAE were not systematically managed because drivers were not well informed about their use [1]. This implies that the generalized ADAS technology does not provide sufficient guidance to drivers to ensure safe driving compared with high-level ADSs.

Therefore, this study explores a user-friendly method of applying the concept of ODDs used in AVs to ADAS-equipped vehicles to provide better guidance to drivers. User manuals of vehicles sold in Korea between 2016 and 2021 were acquired. The target vehicles in this study were equipped with ADAS corresponding to levels 1 and 2 defined by SAE. The manuals of ADAS-equipped vehicles were reviewed, and the presentation of content related to the ODD was scrutinized. Based on the analysis, guidelines for presenting ADAS functions in user manuals for drivers are individually suggested to manufacturers and governments for improving the driving safety of ADAS-equipped vehicles.

2. Literature Review

2.1. Current Status

2.1.1. Definition of ADAS. The ADAS technology assists drivers in driving tasks, thereby increasing driving safety and efficiency. Although ADAS can enhance driver comfort, the primary purpose of this technology is to ensure safety [7]. ADASs correspond to automated driving technology classification levels 1 and 2 of SAE with the driver as the driving subject. Although ADAS functions are similar for all vehicle manufacturers, their names and performances differ.

The most common method for recognizing the functions and limitations of ADAS technology in vehicles is to read the manual provided by the vehicle manufacturer [8]. Most manuals present the limitations of ADAS technology in the form of "restrictions" or "cautions." The manuals also state that ADAS technology may not operate accurately under certain circumstances depending on weather, lighting, roads, lane markings, and other features.

2.1.2. Types of Commercialized ADAS Functions. In this study, commercialized ADASs were classified based on their functions into systems that ensure driving safety, driving convenience, parking safety, and parking convenience. Table 1 lists certain examples of ADAS functions and their classifications.

2.1.3. Concept of ODD. ODD defines a specific operating environment to identify the conditions under which ADSs can operate normally and safely. The ODD includes the operational limits of the subject ADS, safe driving conditions, and driving conditions, such as road type, specific time, weather, and communication environment. The J3016 document of SAE defines ODD as follows [6]:

> "Operating conditions under which a given driving automation system, or feature thereof, is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics."

In other words, the ODD is an environment where an ADS can be stably used. To standardize the ODD, the Automated Vehicle Safety Consortium (AVSC) of SAE, Public Available Specification (PAS) 1883 of the British Standard Institution (BSI), and National Highway Traffic Safety Administration (NHTSA) defined the ODD and classified its elements [9].

The AVSC of SAE developed an ODD framework for the operation and maintenance of AVs. The ODD framework was developed to establish standardized details and a scope that could be understood by ADS developers, testers, and distributors. The AVSC defines ODD using both top-down and bottom-up methods [6].

The BSI first published a taxonomy of ODDs and aimed to provide common terms for describing operating conditions, such as driving situations and environments, to enable automated driving. The BSI classifies ODD in a hierarchical form using scenery, environmental conditions, and dynamic elements as the major categories [10].

NHTSA presents a framework for evaluating specific features of automated driving technology. Particularly, the ODD was classified into six elements, namely, physical structure, operation limit, object, communication, environmental conditions, and zone, such that the operable ODD range could be identified for ADS levels 3–5 [11]. NHTSA provides guidelines for AV development through "automated driving systems: a vision for safety 2.0." This guideline specifies that AV developers should conduct simulations and on-road tests that consider ODD for safety verification [12].

2.2. Previous Studies

2.2.1. ODD Analysis. Gyllenhammar et al. [13] reported a framework for safe operational conditions of ADSs. Initially, they generated use cases by considering the environment in which the ADSs would be used. Subsequently, an ODD that included the environments depicted in the use cases was specified; however, the ODD was modified when

Table 1: Examples of ADAS functions.

Types	Classifications	Examples of functions
Driving safety	Collision warning and avoidance	Safety distance warning (SDW), front vehicle start warning (FVSW), forward collision warning (FCW), forward collision-avoidance assist (FCA), blind spot monitoring (BSM), and collision-avoidance system
	Lane departure prevention	Lane departure warning (LDW), lane change collision warning (LCW), lane-keeping assist (LKA), centering lane-keeping assist (CLKA), lane-following assist (LFA), autosteer, and autolane change
	Driving and speed control	Autonomous emergency braking (AEB), manual speed-limit assist (MSLA), signal detection, automatic postcollision braking system, and city braking system (CBS)
	Headlight control	Low-beam assist (LBA) and night vision (NV)
Driving convenience	Driving assistance and cruise control	Adaptive cruise control (ACC), smart cruise control (SCC), navigation-based SCC (NSCC), navigation on autopilot on the highway, and highway-driving assist (HDA)
Parking safety	Collision prevention assistance	Surround view monitor (SVM), safe exit assist (SEA), rear cross-traffic collision warning (RCCA), and reverse parking collision-avoidance assist (RPCA)
Parking convenience		Parking distance warning (PDW), remote smart-parking assist (RSPA), autopark, summon, and the intelligent parking assist system (IPAS)

a use case deviated from it. The use case and ODD were set using this process. Finally, the primary categories of ODD were determined, including dynamic elements, scenery, connectivity, actions and events, other actors, goals and values-permanent, goals and values-transient, functional range, and fallback ready user.

Czarnecki [14] revised the method for setting the ODD classification criteria using SAE. As SAE emphasizes the necessity for monitoring ODDs, a restricted operational domain (ROD) was defined as a superordinate concept of ODD. Czarnecki [14] suggested that the use of an ADS should be limited by establishing an ROD when a defect occurs in an AV when driving, which affects the object event detection and response of the AV. Furthermore, a degraded operation mode involving a faulty vehicle was defined and the ROD monitoring was presented to determine the application status of ROD as a system architecture [14].

2.2.2. Vehicle Manual Analysis. Oviedo-Trespalacios et al. [1] analyzed user manuals provided to drivers to ensure the safe use of ADAS. They analyzed the differences in the content and readability of ADAS-related information in the manuals of vehicles with high sales in Australia. Seven themes were identified in the manual, including notification of differences, familiarization, operational limits, potential ADAS errors, behavior adaptation warnings, confusion warnings, and malfunction warnings. The analysis results indicate that most manuals warrant a lengthy duration of the study to be understood by the general audience and that they contain numerous confusing texts and infographics. Moreover, regulators and stakeholders from the industry should participate in reducing the discrepancy caused by the lack of standardization in terms of both content and information delivery.

Capallera et al. [15] analyzed the factors affecting ADAS and the limitations of manuals by examining different models from 12 luxury vehicle manufacturers. Herein, the factors affecting ADAS were similar to those of ODD suggested by SAE. The factors comprised six major categories, namely, natural environment, human factors, roads, lanes, obstacles, and vehicle conditions, and 26 subcategories. The results indicate that except for certain common elements, most manuals do not communicate the information clearly. Furthermore, they determined that the limitations of ADAS should be presented more comprehensibly. Additionally, human-machine interaction (HMI) should be used to communicate the unsafe implementation of ADAS.

Ito [9] reported that no standard method exists for describing the ODD of AVs and only a few elements (e.g., the external environment and existing ODDs) should be connected to the ADS. Additionally, as the content must be understood by each user, documents describing sODD should provide appropriate information in terms of safety and maintain consistency with standards and guidelines.

2.2.3. Summary. Several definitions of ODD and various analytical methods have been proposed in previous studies. The definition and presentation of ODDs can be examined by analyzing vehicles' user manuals. A review of previous studies revealed that despite diverse classification criteria for ODDs, the ODD of ADAS is not clearly presented in user manuals. Moreover, the functions and limitations of ADAS are not easily recognized from the driver's perspective when using the manual.

Therefore, the subsequent sections of this paper define the essential and additional elements of ODD by analyzing various ODD definitions and user manuals. Additionally, the presentation of ODDs for ADAS is analyzed by examining the user manuals of vehicles sold in Korea. Based on the analysis, this study proposes guidelines for governments and manufacturers to deliver clear information to consumers regarding ADAS functions. Furthermore, guidelines have been provided to drivers for the efficient use of ADAS technology.

2.2.4. Analysis of ODD Classification and Presentation. This section presents two analyses. First, an ODD classification analysis was performed to identify the essential and additional elements of ODD by comparing the classification criteria and content associated with ODDs of the SAE, BSI, and NHTSA, which are representative organizations that define the ODD elements and limitations of ADSs. The ODD elements that must be explained in the user manual were defined by deriving the essential and additional elements. Second, an ODD presentation analysis was performed to examine the relative importance of ODD elements and presentation methods. The frequency of ODD elements expressed in user manuals was calculated, and the importance of the ODD elements provided by vehicle manufacturers to drivers was examined. Finally, the methods for presenting the driver with the limitations and operating conditions of ADAS in the manuals were investigated.

2.3. Analysis of ODD Classification

2.3.1. Characteristics of ODD. Various international organizations have attempted to standardize ODD. In this study, the ODD classifications of SAE, BSI, and NHTSA were compared.

According to the SAE J3016 document, ODD restrictions must be applied to automated driving levels 1–4, and in areas outside the ODD, drivers must perform dynamic driving tasks. However, the ODD is not clearly defined for automated driving levels 0–2.

The BSI defines the requirements for minimum hierarchical classification in its PAS-1883 document to establish an ODD for the safe use of ADSs. Herein, the ODD aims to provide a general classification system for all environments in which automated driving technologies are tested or used. The document presents the hierarchical classification requirements for ODDs based on automated driving levels 3 and 4 that are also applicable to ADAS. Additionally, the document states that ODD elements should be established based on a mutual agreement between manufacturers and stakeholders and compliance with ODD must be verified via monitoring. The document provides examples for specifying an ODD for each ADS, and they are presented in the ODD definition checklist and text formats [6].

The BSI ODD classification was established in a top-down manner, with seniority, environmental conditions, and dynamic elements considered as major categories. The classification comprised 108 elements in 10 and 21 subcategories [10].

NHTSA presents a framework for evaluating specific functions for the development of ADSs [11]. Particularly, a taxonomy is presented for levels 3 and 4 in AVs to verify whether the ADSs operate within an ODD. The NHTSA ODD classification system is defined in the hierarchical form of upper and lower categories, with each category comprising classes. Additionally, various ODDs provide an identifiable and structured approach. Physical infrastructure, operational constraints, objects, environmental conditions, connectivity, and zones are identified as the major categories. This classification comprises 138 elements in 20 subcategories.

2.3.2. Determination of Essential and Additional ODD Elements. As explained earlier, ODDs are defined differently depending on the organization. The SAE defines the necessity and degree of application of an ODD for each ADS level. The BSI defines an ODD for vehicle manufacturers and stakeholders, whereas NHTSA defines an ODD for the assessment and development of ADSs. However, common classifications and elements have been identified in diverse ODD systems presented by various organizations. Therefore, in this study, the ODD elements commonly classified by at least two organizations were considered essential elements, and the remainders were deemed additional elements. The SAE's ODD framework has been identified as somewhat general in its categorization, with a noted limitation in its failure to reflect specific subelements such as "vehicle entry and egress" [16]. Additionally, because the BSI's ODD framework is defined in the format of a standard, it lacks clear hierarchical structuring among the major ODD categories, which may result in complexity for the general public to understand. Therefore, we have summarized the essential and additional elements based on the NHTSA's ODD framework, which is well structured in terms of categorization hierarchy and more accessible for the public to comprehend.

The essential ODD elements include most of the elements that are typically defined by both NHTSA and SAE. The primary categories of essential ODD elements are physical infrastructure, operational constraints, objects, environmental conditions, connectivity, and zones. Table 2 lists the classification comprising 110 essential elements in 22 subcategories.

Additional ODD elements are those included in the ODD system of only one organization; Table 3 lists the additional ODD elements.

As summarized in Table 3, the ODD elements of NHTSA, SAE, and BSI differed in most of the primary categories, except "zones." The additional elements in the physical infrastructure indicate differences in a few subcategories, including the roadway type, roadway surface, roadway edge, and roadway geometry; BSI defines most of these elements. In fact, BSI provides a finer breakdown of the elements than other organizations. This is because the recognition ranges of the LiDAR and camera based on the pavement material of the road are important for classification in BSI.

2.4. Analysis of ODD Presentation

2.4.1. User Manual Acquisition. The readability of user manuals of major vehicle manufacturers in several countries is unsatisfactory. Furthermore, the methods that express technical limitations differ among manufacturers. Therefore, manuals for the latest vehicles were acquired in this study, including those of 31 vehicle models from 15 manufacturers (Table 4).

2.4.2. Analysis of Exposure Frequencies of ODD Elements. If a vehicle manufacturer explains any ADAS-related ODD element in the user manual, it is assumed that the manufacturer considers the element sufficiently important to provide its information to drivers. Furthermore, if an ODD element is frequently mentioned in the manual, it is assumed that the manufacturer considers the element to be more important than others. Therefore, in this section, the exposure frequencies of the ADAS-related ODD elements expressed in each user manual are calculated.

ODD elements with high exposure frequencies were those that were mentioned in more than one-half (16 or more manuals) of the 31 user manuals, and the exposure frequencies of these elements are summarized in Table 5. Table 6 lists ODD elements with low exposure frequencies, including the elements that are not mentioned in the manuals. For ease of reference, the classifications used previously for essential and additional elements are listed in Tables 5 and 6.

The results indicate a clear difference in ODD elements with high and low exposure frequencies. The analysis of exposure frequencies of ODD elements revealed that similar to the findings of Capallera et al. [15], most manuals do not clearly communicate the necessary information. Out of 31 manuals analyzed, only 31 out of 110 essential ODD elements were explicitly mentioned in more than 16 manuals.

2.4.3. Analysis of ODD Presentation in Manuals. The presentation of ADAS-related ODDs in manuals was investigated. The manuals selected for the analysis were those that specified more than 55 of the 110 essential ODD elements summarized in Table 2.

The ODD can be presented as the following four primary approaches: (1) specifying the operating conditions, (2) expressing through "warning" and "caution" remarks, (3) organizing the "limitations" section, and (4) explaining situations in which ADAS functions cannot be operated within the purview of its description.

First, the operating conditions described in the manual of the Accord Hybrid Touring of Honda Motors were

Table 2: Essential ODD elements.

Primary categories	Subcategory	Elements
Physical infrastructure	Roadway type	Divided highways, undivided highways, high-occupancy vehicle lanes, on/off ramps, one-way roads, turn-only lanes, private roads, reversible lanes, and intersections
	Roadway surface	Asphalt, concrete, grating, dirt, gravel, potholes, and grass
	Roadway edge	Line markers, temporary line markers, paved or gravel shoulder, grass shoulder, grating, rails, curb, cone, and concrete barriers
	Roadway geometry	Straightways, curves, lateral crests, corners, negative obstacles, and lane width
Operational constraints	Speed limit	Minimum and maximum speed limits (absolute, relative to the speed limit, and relative to surrounding traffic)
	Traffic condition	Minimal traffic and normal traffic
Objects	Signage	Signs, traffic signals, crosswalks, railroad crossing, stopped buses, construction signage, first responder signals, distress signals, roadway user signals, and hand signals
	Roadway user	Vehicle types, stopped vehicles, moving vehicles (manual and autonomous), pedestrians, and cyclists
	Nonroadway user obstacle/object	Animals (e.g., dogs and deer), shopping carts, debris (e.g., pieces of tire, trash, and ladders), construction equipment, pedestrians, and cyclists
Environmental conditions	Weather	Wind, rain, snow, sleet, and temperature
	Weather-induced roadway condition	Standing water, flooded roadways, icy roads, and snow on roads
	Particulate matter	Fog, smoke, smog, dust/dirt, and mud
	Illumination	Day, night, and twilight
Connectivity	Vehicle	V2V communications (e.g., DSRC and Wi-Fi) and emergency vehicles
	Traffic density information	Crowdsourced data (e.g., Waze) and V2I
	Remote fleet management system	A vehicle may be supported by an operation center capable of performing remote operation
	Infrastructure sensor and communication	Work zone alerts, vulnerable road users, routing and incident management, GPS, 3D high-definition maps, pothole locations, weather data, and data on the cloud
Zones	Geofencing	Central business districts, school campuses, and retirement communities
	Traffic management zone	Temporary lane closures, dynamic traffic signs, variable speed limits, temporary or nonexistent lane markings, human-directed traffic, and loading/unloading zones
	School/construction zone	Dynamic speed limits, erratic pedestrians, and vehicular behaviors
	Regions/states	Any legal, regulatory, enforcement, tort, or other considerations
	Interference zones	Tunnels, parking garages, dense foliage, limited GPS owing to tall buildings, and atmospheric conditions

Note. V2V: vehicle-to-vehicle; DSRC: direct short-range communication; GPS: global positioning system; 3D: three-dimensional.

Table 3: Additional ODD elements.

Primary categories	Subcategory	Elements
Physical infrastructure	Roadway types	Emergency evacuation routes, motorways, radial roads, distributor roads, minor roads, slip roads, and shared spaces
	Roadway surfaces	Mixed, brick, scraped road, partially occluded, and speed bumps
	Roadway edges	Concrete barriers and lane type
	Roadway geometry	Hills, horizontal plane, transverse plane, longitudinal plane, number of lanes, roundabouts (normal, compact, double, large, and mini), and junctions (T-junctions, staggered, Y-junction, crossroads, and grade separated)
Operational constraints	Traffic conditions	Density of agents, flow rate, and agent type
Environmental conditions	Weather-induced roadway conditions	Haze
	Particulate matter	Surface contamination
	Illumination	Headlights
Connectivity	Infrastructure sensors and communication	Galileo global navigation satellite system

Table 4: Vehicle models acquired for the analysis.

Manufacturers	Vehicle types	Model
Audi	Passenger car SUV/RV	S8 L RS Q8
BMW	Passenger car SUV/RV	Series 7 X7
Porsche	Passenger car SUV/RV	911 Turbo S, 718 Boxter GTS 4.0, and Taycan Turbo S E3 Cayenne Turbo, Macan GTS
Daimler truck	MPV Truck	Sprinter-3 19KB Sprinter-3 19FG, Sprinter-5 19FG, and Actros
Man	Truck	TG
Tesla	Passenger car SUV/RV	Model S Model X
Stellantis	SUV/RV	Grand Cherokee Summit
Scania	Truck	S650A6X2
Volvo	Truck	FH 540hp
Jaguar Land Rover	SUV/RV	RangeRover 5.0SC
Honda	Passenger car SUV/RV	Accord Hybrid Touring CR-V Hybrid Touring and Odyssey Elite
Hyundai	Passenger car	G80
Hyundai-Kia	MPV Truck	Universe Xcient
GM	Passenger car SUV/RV Truck	The New Malibu Chevrolet Traverse Colorado Z7-1
SsangYong	SUV/RV	Rexton

Note. SUV: sports utility vehicle; RV: recreational vehicle; MPV: multipurpose vehicle.

Table 5: ODD elements with high exposure frequencies.

Primary categories	Subcategory	Element	Exposure frequency
Physical infrastructure	Roadway type	Highway	26
		Intersection	18
	Roadway surface	Gravel	17
	Roadway edge	Line marker	16
		Concrete barrier	24
		Rails	25
		Curb	16
	Roadway geometry	Curve	28
		Lateral crest	23
		Corner	25
		Negative obstacle	25
		Lane width	20
Operational constraint	Speed limit	Maximum speed	27
		Minimum speed	31
Object	Roadway user	Pedestrian	23
		Cyclist	25
	Nonroadway user obstacle/object	Animal	27
		Debris	24
Environmental condition	Weather	Wind	18
		Rain	28
		Snow	29
		Temperature	17
	Weather-induced roadway condition	Standing water	26
		Icy road	22
	Particulate matter	Fog	25
		Dust/dirt	17
	Illumination	Day	17
		Night	19
		Headlight	17

Table 5: Continued.

Primary categories	Subcategory	Element	Exposure frequency
Zone	Interference zone	Tunnel	16
		Parking garage	18

Table 6: ODD elements with low exposure frequencies.

Primary category	Subcategory	Element	Exposure frequency
Physical infrastructure	Roadway type	One way	2
	Roadway surface	Asphalt	1
		Concrete	1
		Grating	2
	Roadway edge	Shoulder	1
Objects	Signage	Crosswalk	0
		Railroad crossing	2
Environmental condition	Weather-induced roadway condition	Flooded roadway	1
Connectivity	Vehicle	DSRC	0
		Wi-Fi	2
	Traffic density information	V2I	0
	Infrastructure sensor and communication	Work zone alert	1
		Vulnerable road user	2
		Routing and incident management	0
		Pothole location	2
		Weather data	0
Zone	Geofencing	CBD	0
		School campus	0
	Traffic management zone	VMS	3
		Dynamic traffic sign	0
		Temporary or nonexistent lane markings	3
		Loading/unloading zone	3
	School/construction zone	Dynamic speed limit	0
		Erratic pedestrian and vehicular behavior	1

Note. DSRC: direct short-range communication; CBD: central business district; VMS: variable message sign.

analyzed. This method describes a situation in which ADAS functions can be operated and are familiar to drivers. However, this presentation method mentions only those ODD conditions that can be operated and does not describe situations or restrictions that may be dangerous when using the ADAS functions.

Second, the manuals of the Audi S8L, Porsche 911 Turbo S, Hyundai-Kia Universe, and BMW Series 7 that correspond to expressing "warning" and "caution" remarks were examined. This method primarily expresses the limitations of ADAS and the dangerous situations that may occur during driving. However, as the warning is written as "may not work" and the method does not correctly describe the ODD, drivers cannot easily recognize the ODD.

Third, the manuals of the Hyundai G80 corresponding to organizing the "limitations" section were considered. Herein, drivers can easily recognize and understand the ODDs as they are organized using ADAS technology. However, the relevant section vaguely specifies the ODD as "the elements that influence include, but are not limited to, the following."

Finally, the manual of the Daimler Truck E3 Cayenne Turbo was analyzed. In this method, drivers can recognize an ODD and the limitations of the ADAS functions under the premise that they are capable of completely understanding all function descriptions. However, the ODD of ADAS is vaguely specified in this method and the description of the technology is prioritized over its technical limitations. Figure 1 depicts examples of the aforementioned four methods.

The aforementioned presentations indicated that most manuals explain the ODD based on "warning" and "caution" remarks. The first presentation method explained the ODD in the most comprehensible manner as it was described in a separate section after the function description of the ADAS and comprised more ODD-related information than the other methods. However, the majority of limitations are presented ambiguously with phrases such as "can be used," "may not be," and "may not operate." This could lead to difficulties in clearly recognizing the situations in which ADAS can function.

2.4.4. Summary. The essential and additional elements of ODD were identified by performing ODD classification. Furthermore, the exposure frequency of ODD elements and presentation methods were analyzed.

The analysis indicated that vehicle manufacturers are attempting to present the ODDs of ADAS to drivers using

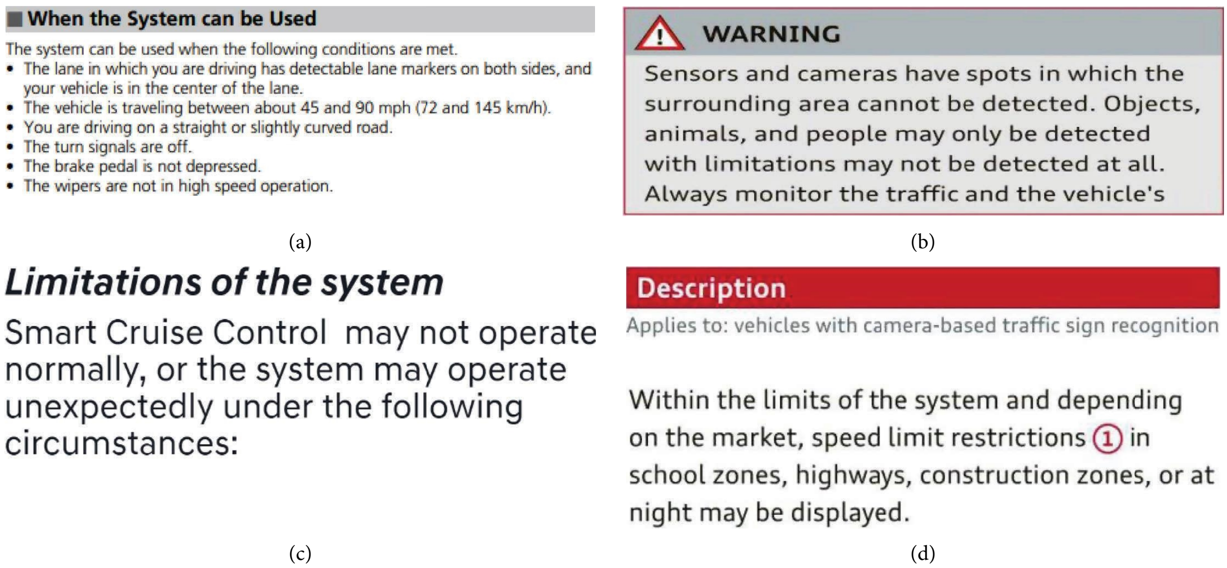

Figure 1: Examples of operation design domain (ODD) presentation. (a) Method of specifying the operating conditions. (b) Method of expressing via "warning" and "caution" remarks. (c) Method of organizing the "limitations" section. (d) Method of explaining situations in which ADAS functions cannot be operated. Sources: manuals of the 2022 Honda Accord Hybrid, 2021 Audi A8, 2021 Hyundai Genesis G80, and 2021 Audi A8.

various methods. The analysis of ODD presentation reveals that the presentation of ADAS's ODD is often couched in ambiguous terms regarding limitations and performance, with phrases such as "can be used," "may not operate normally," and "may operate unexpectedly." Furthermore, the inconsistency in ODD presentation and the representation of ODD limitations are likely to cause confusion among ADAS users, as indicated in [1, 9].

In conclusion, the manuals contain only a few of the essential ODD elements, which are not presented clearly to enable drivers to recognize the ODDs. Therefore, a standard method for presenting ODDs in the manuals must be established to ensure that drivers can easily recognize the operational limitations of ADAS functions in terms of ODDs.

2.5. ODD Presentation Guidelines for Improving ADAS Safety. The ODD presentation guidelines for ADAS-equipped vehicles were obtained based on the trend analysis of ODD-related regulations for ADSs. Subsequently, ADAS-related ODD presentation guidelines for manufacturers, governments, and consumers were determined.

2.5.1. Trend Analysis of ODD-Related Regulations for ADSs. The commonalities and differences in the ODD-related regulations enacted in Europe, the United States, and Korea were analyzed.

2.5.2. ODD Legislation Trend in Europe. The European Union requires AVs to be driven in the operational domain (OD) while considering road conditions, geographical areas, environmental conditions, and speed ranges. In addition, vehicle manufacturers should provide AV users with information on the operational conditions of the system, OD scope, and functional limitations in an easily understandable format [17].

2.5.3. ODD Legislation Trend in the U.S. A policy introduced by NHTSA in 2016 [12] specifies that manufacturers and the Department of Transportation should clearly specify ODDs, including the roadway type, geographical location, speed range, lighting conditions for operation, and weather conditions. Additionally, the manuals provided by manufacturers stipulate that the function, performance, and ODD of the ADS must be clearly indicated and the state in which the ADS cannot be operated must be specified.

A document issued by NHTSA in 2018 [11] specifies that ODDs should be considered when testing automated driving technologies. However, the document is a report that systematically presents experimental examples of automated driving technology and does not serve as a regulation.

2.5.4. ODD Legislation Trend in Korea. According to Article 111-3 (designation of operable areas for ADSs) of the Korean "rules on the performance and standards of automobiles and auto parts," vehicle manufacturers must specify drivable areas where AVs can be operated. These regulations require vehicle manufacturers to specify the driving environment, such as the road and weather conditions, operating limits of the ADS, and other information related to the safe operation of the vehicle in drivable areas.

Additionally, according to the safety standards for partially automated driving systems corresponding to the aforementioned regulations, such systems should respond to the operable area specified by the manufacturer during operation. Otherwise, the driver must be allotted sufficient time to assume control of the ADS. The partially automated driving system must automatically adjust the vehicle speed based on environmental conditions to comply with the ODD specified by the manufacturer.

2.5.5. Summary. Both the European and U.S. regulations state that the documentation provided by the manufacturer must include ODD-related elements of an ADS. Furthermore, a definition of ODDs must be provided in Europe, the U.S., and Korea along with the elements to be included, such as the roadway type and weather conditions. However, unlike in Europe and the U.S., no regulation has been established in Korea that requires ODD-related elements to be included in the documents provided by manufacturers. Furthermore, drivers are not mandated to recognize and focus on the limitations of automated driving technology. Therefore, similar to the European and U.S. regulations, the content must be presented in Korean laws and regulations, which will enable vehicle manufacturers and drivers to easily recognize the functions and limitations of automated driving technology.

2.6. Guidelines for ADAS-Related ODD Presentation. Vehicle manufacturers must efficiently communicate the capabilities and limitations of ADAS to drivers. However, the analysis of the ODD presentation indicated that the essential ODD elements suggested by various organizations are not clearly presented. Although various countries follow certain regulations for specifying the ODD in the manuals, they are not yet standardized. In other words, manufacturers fail to clearly present the items to be specified because of ambiguous rules and the responsibilities of manufacturers and consumers are not easily distinguished. As consumers do not possess a clear understanding of ADAS and may not be aware of its limitations, traffic accidents may occur when ADAS technology is used in situations where its utilization is not feasible. Therefore, this section proposes ADAS-related ODD presentation guidelines for manufacturers, governments, and drivers.

2.6.1. Guidelines for Vehicle Manufacturers. The ODD presentation guidelines for vehicle manufacturers can be summarized as follows:

Guideline 1: in the user manual, the vehicle manufacturer must specify a certain classification based on ADAS functions to clearly present the purpose of their use and facilitate understanding

Guideline 2: the vehicle manufacturer must clearly present the ADAS functions, limitations, and ODD in the user manuals in the formats presented in Tables 7 and 8

Guideline 3: when ADAS cannot be implemented owing to the failure of vehicle equipment or system errors, the vehicle manufacturer must inform the driver of the newly restricted ODD via HMI

Typically, ODDs are presented in two formats (Tables 7 and 8). However, the vehicle manufacturer may modify the format, if required, to ensure convenience to drivers. As specified in the guidelines, vehicle manufacturers should aim to explain the ADAS functions, limitations, and ODDs as clearly as possible in the user manuals in the recommended formats.

Most user manuals present the ADAS functions comprehensively. However, only a few methods are available for delivering an ODD for each function. Therefore, the format presented in Table 7 can be used to verify the ODD of each ADAS function installed in the vehicle. This enables the verification of essential and additional ODD elements based on the ADAS function. Table 7 presents the essential and additional elements of the subcategory “roadway type” from the primary category “physical infrastructure.” Four key ADAS technologies in the driving-safety field of the Hyundai Motor G80 are selected as examples.

Table 7 summarizes the manner in which the individual functions of the ADAS operate for each ODD element. An ADAS function operating in the entire environment in a manner that corresponds to a certain ODD element is indicated by “O.” If a function operates only in certain environments and does not operate in any environment, it is indicated by “△” and “X,” respectively. However, in Table 7, only “△” and “—” are indicated because the ODD presentation is not clearly described in the Hyundai G80 user manual; here, “—” is used to denote the absence of an explanation (Table 7).

Considering an example from Table 7, if the curvature of a curve is extremely large or small, a navigation-based smart cruise control (NSCC) system may not function as intended.

Table 8 may be used to describe individual ADAS functions to convey the contents presented in Table 7 more effectively; this format can be placed at the bottom of a section in a user manual. This format provides easily comprehensible and specific examples of driving and nondriving situations based on the method used by BSI. Additionally, the familiarity of the format to consumers ensures that ODD-related information can be easily recognized. Table 8 presents an example prepared based on forward collision-avoidance assist, which is an ADAS function of the G80 of Hyundai Motors. After analyzing the user manual, only the essential elements of “physical infrastructure” are presented to indicate both driving and nondriving situations. Although the manual of Hyundai’s G80 contains a few ODD-related elements, it does not offer high specificity; therefore, the ODD must be presented in more detail than the example presented in Table 8.

The AVs restrict the ADAS functions when traveling outside the ODD, which should be informed to the driver. Therefore, HMI should be utilized to ensure that drivers are aware of the functional limitations of ADAS technology and the newly restricted ODD, as suggested in [12, 13].

2.6.2. Guidelines for Governments. The guidelines for ODD presentation to the government can be summarized as follows:

Guideline 4: to rationally promote the stable development of ADAS and driving safety, proposals from

Table 7: ODD presentation format 1.

Primary category	Subcategory	Element type	Element	Driving safety FCA	LKA	SCC	NSCC
Physical infrastructure	Roadway types	Essential	Divided highway	—	—	—	△
			Undivided highway	—	—	—	—
			High-occupancy vehicle lane	—	—	—	—
			On/off ramps	△	△	△	△
			One way	—	—	—	—
			Turn-only lanes	△	△	△	△
			Private roads	—	—	—	—
			Reversible lanes	—	—	—	—
			Intersections	△	△	△	△
			Emergency evacuation routes	—	—	—	—
		Additional	Motorways	△	△	△	△
			Radial roads	—	—	—	—
			Distributor roads	—	—	—	—
			Minor roads	△	△	△	△
			Slip roads	△	△	△	△
			Shared spaces	—	—	—	—

Note. FCA: forward collision-avoidance assist; LKA: lane-keeping assist; SCC: smart cruise control; NSCC: navigation-based SCC.

Table 8: ODD presentation format 2.

Primary category	Subcategory	Description	Contents
Physical infrastructure	Roadway type	Drivable area	Divided highways, undivided highways, high-occupancy vehicle lanes, one way, private roads, and reversible lanes
		Undrivable area	FCA may not function accurately when driving on on/off ramps, turn-only lanes, intersections, motorways, minor roads, and slip roads

Note. FCA: forward collision-avoidance assist.

various organizations should be considered and the presentation of ODDs must be standardized

Guideline 5: relevant laws must be enacted such that vehicle manufacturers can specify the ODD in the manuals and set the format

Guideline 6: ensure that consumers are aware of ADAS technology and vehicle performance and are accountable when enacting legislation

Guideline 7: campaigns and educational programs should be conducted to benefit the public

The standardization of ODD presentation facilitates the consideration of the opinions of various research institutes and international organizations and enables accountability of both manufacturers and consumers, as presented in the U.S. Vehicle Safety Act. Additionally, considering the Enforcement Rules of the Traffic Safety Act of Korea, the standards for writing manuals can be set in a form similar to the laws proposed for digital tachographs.

2.7. Guidelines for Drivers. The guideline for ODD presentation to drivers can be summarized as follows.

Guideline 8: drivers should not solely rely on ADAS and must understand its functions, limitations, and ODD by reading the manufacturer's manual.

Several studies have reported that traffic accidents caused by complete reliance on automated driving technology may increase. Therefore, drivers should recognize and focus on the functions, limitations, and ODD when using ADAS technology by understanding the information presented in the user manuals.

3. Conclusions and Future Research

3.1. Conclusions. The popularization of low-level automated driving technologies, such as ADAS, has significantly reduced traffic accidents. However, in recent years, the number of traffic accidents caused by the complete reliance on automated driving technology and driver negligence has increased. In addition to driver negligence, vague and unclear guidance pertaining to ADAS usage in user manuals also contributes to the aforementioned problem. Therefore, this study presents guidelines for manufacturers, governments, and consumers to increase safety when using the ADAS.

As ODDs are directly associated with the safety of automated driving technology, the trends of ODDs from international organizations were analyzed. After accumulating the concepts and elements of ODDs presented by SAE, BSI, and NHTSA, the essential and additional ODD elements were defined.

A frequency analysis of the ODD elements in the manuals revealed that most manuals specified approximately 60 ODD elements. Approximately 100 essential ODD elements exist, which must be supplemented. Furthermore, an analysis of the ODD presentation method indicated that most manuals specified ODD based on three methods; however, the presentation was vague and unfamiliar to drivers. Therefore, a standardized method for presenting an ODD must be devised to ensure that drivers can easily recognize the limitations of the technology.

Guidelines for presenting ODDs have been presented in this paper to benefit manufacturers, governments, and consumers. Manufacturers should effectively communicate the ADAS functions, limitations, and ODDs to consumers via standardized formats. If the ADAS functions are degraded, only a few ODDs should be communicated via HMI. Additionally, the government should reasonably standardize ODD presentation to promote the stable development of ADAS and driving safety. Consumers should not entirely rely on ADAS technology when driving an ADAS-equipped vehicle and should focus on safety. The consumers should also read the manual to recognize the functions, limitations, and ODD of the technology.

The levels of ODD provided in the technical documents and manuals of ADAS-equipped vehicle manufacturers were analyzed for situations where the classification and items of ODD were not clearly defined. This study presents the basic guidelines to prepare for scenarios where ODDs are clearly defined. The application of the ODD concept to vehicles equipped with ADAS suggested in this study directly affects the driving safety of ADAS-equipped vehicles.

3.2. Limitations and Future Endeavors. As international conventions and concepts pertaining to ODDs are currently being transitioned based on the suggestions of various organizations, the verification process for establishing essential and additional ODD elements for each institution is inadequate. Moreover, although the enforceability of the regulations and laws related to ODDs proposed by various organizations differs, the guidelines consider all proposals that present regulations for enacting the laws and regulations.

In this study, the guidelines established based on the enactment of laws and regulations in the U.S., Europe, and Korea were presented. However, the limitations are that the analyzed manuals are 31 manuals of vehicle manufacturers sold in Korea, and despite existing guidelines that suggest the need to investigate the display of ODD restrictions through HMIs, this aspect was not researched. In the future, it is necessary to collect more manuals for various vehicle types and conduct research on presenting, displaying, and standardizing ODDs from various aspects to standardize integrated ODDs. This will provide more systematic guidelines for the effective use of ADAS-equipped vehicles.

Data Availability

The car user manual used in this study can be downloaded from each car manufacturer's website.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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