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Driver Behavior Model to Define a Preventable Boundary for Scenario-based Safety Evaluation of Automated Driving

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ABSTRACT: Automated Driving Systems (ADS) possess a clear potential to solve various social issues. UN WP29 published a framework document mandating that ADS to prevent reasonably foreseeable and preventable injuries within their Operational Design Domain (ODD). Therefore, the development of precise methods to define both reasonably foreseeable and preventable collisions stands as a pivotal concern. This research provides an engineering framework aimed at elucidating test scenarios based on two distinct boundaries. The proposed fundamental concept facilitates the derivation of a specific human driver behavior model through the deconstruction of driver maneuvers into detailed processes and parameterizing them based on pertinent evidence. Consequently, through the manipulation of driver behavior assumptions, various preventable boundaries can be defined corresponding to two aspects of ADS transformation in accordance with safety evaluation scenarios.

KEY WORDS: Safety assurance, Scenario-based safety evaluation, Reasonable foreseeability, Preventability

1. Introduction

Automated Driving Systems (ADS) possess a clear potential to solve various social issues, including mitigating traffic accidents, alleviating traffic congestion and addressing the shortage of professional drivers. To ensure acceptable safety for multiple stakeholders, UN WP29 published a framework document(1) mandating that ADS prevent reasonably foreseeable and preventable injuries within their Operational Design Domain (ODD). However, this document does not specific a particular scientific approach to define reasonable foreseeability and preventability. Therefore, the development of specific methods to define both reasonably foreseeable and preventable collisions emerges as a pivotal concern.

The Japanese Ministry of Economic, Trade and Industry has provided support for a research project known as Safety Assurance KUdos for Reliable Autonomous vehicles (SAKURA) since 2017. The SAKURA project(2) presents an engineering framework aimed at elucidating both sufficient and necessary safety evaluation scenarios through the utilization of two distinct boundaries. Numerous research outcomes (e.g. Scenario structures) have been utilized in the development of ISO34502(3) (Test scenarios for automated driving systems Scenario-based safety evaluation framework). Furthermore, UN-R157(4) delineates safety evaluation scenarios for low-speed Automated Lane Keeping Systems (ALKS). These scenarios are derived utilizing methodologies to define reasonable foreseeability(5)(6) and preventability using the competent and careful (C & C) human driver model(4).

Various modeling approaches of have been developed to establish more comprehensive safety criteria based on reasonable human driver behavior. Mattas et al.(7) introduced two fuzzy Surrogate Safety Metrics (the Proactive Fuzzy SSM(PFS) and Critical Fuzzy SSM(CFS)). These metrics enable the calculation of deceleration levels based on both lateral and longitudinal safety checks. Engstrom et al.(8) proposed NIEON (Non-Impaired Eyes ON conflict) reference model, which serves as benchmark for human response timing through the incorporation of the driver's visual looming characteristic. This model is designed to represent the timing of human responses under non-impaired conditions. It is essential to conduct a comparative analysis of each modeling concept and data resource to achieve a harmonization of reasonable safety criteria to define socially acceptable preventability.

The objective of this research involve two main aspects: the proposal of a driver behavior modelling concept to define the preventable boundaries, and the subsequent application of this concept to specific models based on experimental data and real traffic data, corresponding to the respective roles required by ADS.

2. Approach to driver behavior modelling

2.1. Scenario based safety evaluation approach

A total of 24 traffic disturbance scenarios within the highway domain are described in Annex B of ISO34502 (Fig. 1)(3). These scenarios are composed of road geometry, subject vehicle behavior, and the positions and actions of surrounding traffic participants. UN-R157 presents both reasonably foreseeable and preventable scenarios (No. 1/2/4) for the safety evaluation of ALKS(4). Furthermore, undefined parameter ranges of other traffic disturbance scenarios will be updated in accordance with the extension of the ODD of ADS.

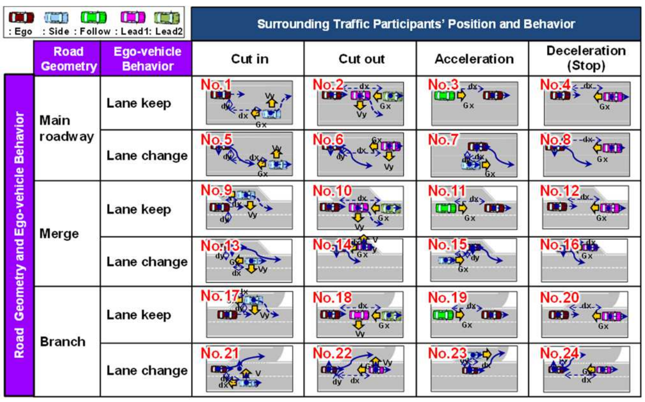


Fig. 1 Scenario structure of traffic disturbance in highway domain

A single safety evaluation criterion cannot be uniformly applies across all 24 traffic disturbance scenarios, given the variability in safety requirements for ADS is varied dependent on respective scenario. In this study, representative scenarios, namely No. 1 and No. 7, have been selected to facilitate a discussion on the distinctions that should be accounted for when establishing safety evaluation criteria.

2.2. Preventable boundary

2.2.1. Two aspects about how to define preventability

Waymo[9] adopted a safety evaluation concept to differentiate between the role of the conflict initiator and that of the conflict responder within conflicts instigated by other road users. This approach suggests the need to establish two distinct methods to define respective preventability in correspondence to these roles.

Specifically, when ADS encounters a critical situation from a cut-in maneuver by another traffic participant, the ADS is required to make its utmost effort to avoid a collision. Therefore, this preventability boundary for such scenarios must be established based on the competent and careful human driver performance (Table 1, scenario No. 1). In contrast, when the ADS independently conducts a lane change maneuver, the ADS is required not only to avoid a collision but also to prevent a interference with the traffic participant approaching from the back. Consequently, this preventability boundary has to be defined by modelling the behavior of a driver approaching from behind, assuming a lack of care and subpar performance. This is essential to ensure the safety of the ADS even when other road users do not exercise adequate attentiveness(Table 1, scenario No. 7).

Table 1 Two aspects about preventability definition

	Responder role ◀ Role inversion ▶	Initiator role
Scenario	No.1 ADS Surrounding vehicle	No.7 ADS Surrounding vehicle
Safety requirement	- Strive to achieve utmost effort for collision avoidance or damage mitigation while surpassing the performance of human driver	- To temporarily withhold lane change to prevent collisions and avoid obstructing the rear vehicle - To complete the lane change appropriately
Research subject	Quantification of **a competent and careful driver behavior**	Quantification about **the subjective experience of the rear vehicle driver's feelings**

2.2.2. Driver behavior models to correspond both aspects

1) Concept of driver behavior model of responder role

Fig. 2 presents an illustration of detailed processes of human driver behavior for collision avoidance toward cut-in maneuver from the other vehicle. These processes are composed of perceptions, decisions, and reactions. It should be noted that this concept assumes a precondition wherein the driver's evasive action is restricted to braking operations. A crucial consideration involves quantifying the essential time interval for the driver to transition between the perception of risk and the subsequent evaluation of that risk, as pertinent to each individual scenario.

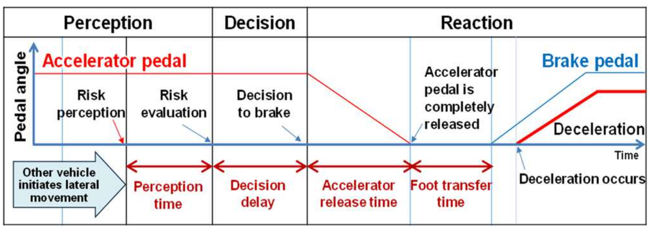


Fig. 2 Driver's evasive behavior processes by a braking operation

For instance, to quantify the necessary time in cut-in scenario immediately after the onset lateral movement by another vehicle, it becomes imperative to ascertain the driver's reaction time. Each pivotal event influencing the driver's risk perception of risk differs according to the impending collision risk posed by the position of the surrounding traffic participants. The driver behavior model corresponding to the role of the responder is utilized to evaluate safety performance of the ADS by comparison with competent and careful human driver.

2) Concept of driver behavior model of the initiator role

As described in 2.2.1, the ADS must assure safety by avoiding both collision and interference with surrounding traffic participants when the ADS conducts a maneuver designed to elicit reactions from other participants. Fig. 3 illustrates the sequential behavioral process of a human driver in a vehicle approaching from behind, used for the safety evaluation of the automated lane change function. These processes are composed of drivers reaction time[sec], average deceleration rate[m/s^2], and minimum final gap time[sec]. Although the fundamental structure is similar to the responder role, there is a distinct difference which requires ADS to ensure the predetermined minimum final margin. Furthermore, it is necessary to determine each parameters necessitates the consideration of evidence indicating the subjective perceptions of ordinary drivers concerning acceptable interference levels.

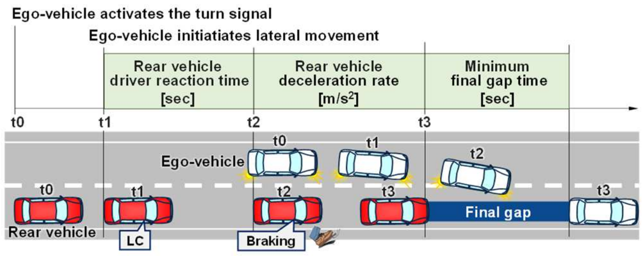


Fig. 3 Human driver's behavior processes of a vehicle approaching from behind

3. Parameterization for driver behavior modelling

3.1. Parameter study through literature review related to surrogate superior driver behavior

Numerous studies and experiments have reported various driver characteristics, elucidating their maximum capability for design of advanced driver assistance systems. Therefore, these findings facilitate the establishment of benchmarks for driver competence, particularly in critical or unavoidable situations. To emulate superior driver performance effectively, this study reviews a range of pertinent parameters documented in research papers that report concrete parameters that indicate specific characteristics of capable drivers.

Many previous studies presented referable parameters through various experiments and investigations under critical situations. For instance, Green[10] has indicated that drivers are capable of perceiving a signal and transitioning their foot from the accelerator to the brake pedal within 0.75 [sec]. Makisita et al.[11] undertook a comparative analysis of the maximum deceleration time required to reach a specified deceleration between trained and regular drivers. Trained drivers exhibited the ability to brake at 0.774 [G] (7.6 [m/s^2]) and reach a maximum deceleration in 0.60 [sec]. NHTSA also reports similar characteristics related to reaction and deceleration by analyzing pre-crash and accident data[12].

3.2. Traffic data acquisition though instrumented vehicles related to vehicle's wandering characteristic during lane keeping

Due to various patterns concerning collision risks, such as abrupt decelerations and cut-ins initiated by other vehicles, drivers do not consistently exhibit uniform behavior. This variability is especially evident when attempting to quantify driver responses to collision risks arising from the side. In order to differentiate between scenarios involving wandering and those involving cut-ins, it becomes essential to delineate driver behavior based on the lateral movement of the other vehicles in adjacent lanes. Real-world traffic data is collected through instrumented vehicles (Fig. 4) and predominantly used to define a reasonably foreseeable parameter range(2). This study uses analyzed trajectories to quantify the distribution of lane wandering widths demonstrated by human drivers during lane keeping with surrounding vehicles. Furthermore, this real-world traffic data is also utilized to analyze actual gap maintained with vehicles behind during lane changes executed by human drivers.

Fig. 4 An instrumented vehicle and a sample of real traffic data

Fig. 5 illustrates the distribution of maximum wandering width observed during lane keeping, derived from is the analysis of real traffic data. The median value of 0.750[m] indicates that drivers of other vehicles tend to execute lateral movements exceeding 0.375[m] when performing lane change maneuvers. Therefore, continuous lateral movement of other vehicle is related to initiate driver risk evaluation to cut-in maneuver closely.

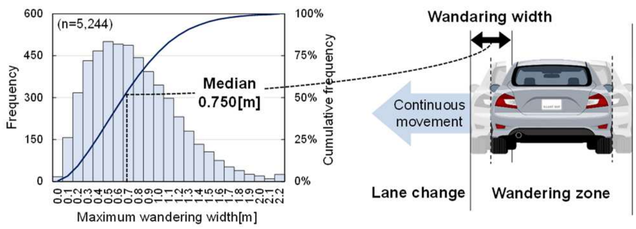


Fig. 5 Distribution of maximum wandering width

4. Driving Simulator experiments

Due to the diverse purposes and intentions of respective experiments, attaining exhaustive evidence for all the required parameters sought in this research proves challenging. An experimental and empirical approach, particularly one centered on investigating driver perception, recognition, and decision making processes throughout a controlled and unified manner, is recommended. In this study, two experiments utilizing Driving Simulator are conducted in order to acquire human drivers behavior data for modelling both aspects of responder and initiator.

4.1 Experimental settings

4.1.1 Experiment 1 (responder role)

The primary purpose of the Driving Simulator experiment 1 is to capture drivers' evasive behaviors, with a specific focus on quantifying the time required by drivers for risk assessment. The experiment involved the participation of a total of 11 ordinary drivers, with an average age : 38.7 (ranging from 25-49 years old). Each participant was tasked with providing their utmost effort in maneuvering to avoid collisions in several hazardous cut-in events (Fig. 6).

The measured data are composed of a range of physical parameters associated with the Ego vehicle, including quantities such as velocity [m/s] (longitudinal/lateral), acceleration [m/s^2] (longitudinal/lateral), operational states (accelerator, brake, steering, and turn signal status). Additionally, the data includes information on the Ego vehicle's relative positioning with respect to surrounding vehicles, denoted by relative distance [m] (longitudinal/lateral) and relative velocity [m/s]. Moreover, a collision risk index is provided, represented by the Time to Collision[sec].

To assess the proficiency of superior driver's evasive behavior, the behavior of each driver is deconstructed into several components. These components include the reaction time towards a cut-in by a surrounding vehicle [sec], the time to transfer foot pedals [sec], the maximum deceleration rate achieved [m/s^2], and the time required to attain the maximum deceleration[sec].

Parameter	Value
Ego-vehicle velocity	100 km/h
Traveling velocity in the adjacent lane	70 km/h
Lateral velocity of cut-in vehicle	1.8 m/s
Time to collision at the onset of the cut-in	3.0 sec

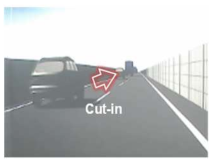
Fig. 6 Outline of Driving Simulator experiment 1

4.1.2 Experiment 2 (initiator role)

Although there are plenty of useful previous references to indicate a competent and careful human driver performance, there is a scarcity of research that aims to quantify the subjective perception of interference from the viewpoint of surrounding traffic participants. According to Japanese Road Traffic Act(13), "obstructing progress" is defined as the act of initiating or sustaining movement in a manner that could potentially compel another vehicle or streetcar to abruptly alter its speed or direction to evade potential danger.

The primary objective of experiment 2 is to capture drivers' behaviors, aiming to quantify parameters for both a relatively careless human driver model and a preferred minimum margin for drivers following behind. This experiment engaged a total of 26 ordinary drivers, with the average age of 42.2 (ranging from 23-61 [y/o]). Additionally, the participants' average annual traveling distance was 13,300 km (ranging from 100-40,000 [km/year]) participated in the experiment. In this experiment, each participant was tasked with freely selecting their preferred collision avoidance behavior during several cut-in scenarios (Fig. 7).

In Experiment 2, the initial time to collision at cut-in start to a value of 5.0 seconds. This deliberate alteration is intended to examine drivers' behaviors within a relatively safer context, in comparison to the conditions present in Experiment 1. Notably, the same log data collection methodology employed in Experiment 1 is utilized in Experiment 2. This consistency in data collection facilitates a direct comparison between the two experiments, as the analysis items targeted in both studies remain identical.



Parameter	Value
Ego-vehicle velocity	120 km/h
Traveling velocity in the adjacent lane	60-110 km/h
Lateral velocity of cut-in vehicle	1.0 m/s
Time to collision at the onset of the cut-in	5.0 sec

Fig. 7 Outline of Driving Simulator experiment 2

Furthermore, the study delves into the driver's preferred minimum forward gap to the preceding vehicle following a lane change. This investigation encompasses a total of 10 driving scenarios, each characterized with different time-headways (0.150-1.125[sec]). The responses of each participant are categorized into 4 distinct types, namely: no reaction, accelerator release, brake operation less than 1.5[m/s^2] brake operation exceeding 1.5[m/s^2]).

4.2. Results

4.2.1 Driver behavior model for responder role (Experiment 1)

1) Driver characteristic of risk evaluation

In the pursuit of studying to research superior driver behavior, it is logical to assume that drivers are prepared to react promptly to collision risks. Thus, a plausible approach involves the analysis of data from the 2nd or subsequent trials, which serves as a foundation for modeling superior driver behavior modelling based on Experiment 1. To this end, a comparison is made between the risk evaluation times observed during the 1st trial (0.80 [sec]) and those during the 2nd or subsequent trials (0.40 [sec]). This comparison aids in estimating the time required for risk evaluation (refer to Fig. 8).Although the result of the 1st trial includes two processes (cut-in recognition events and risk evaluations), the result for the 2nd or subsequent trial can be interpreted as the net risk evaluation time. However, it is important to acknowledge that the current findings might not yet provide a comprehensive and definitive conclusion. As such, the acquisition and analysis of additional experimental data are necessary to be more accountable and certain evidence.

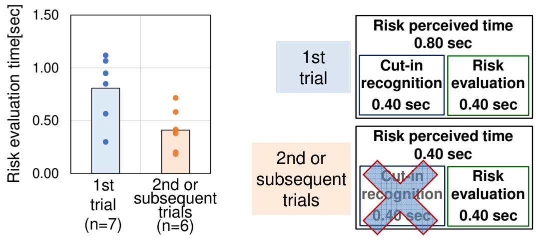


Fig. 8 Comparison of risk evaluation time between 1st trial and 2nd, or subsequent trial

2) Competent and careful driver behavior model

Fig. 9 portrays a driver behavior model for a competent and careful human driver's performance based on previous research and data obtained by Experiment 1. Within this model, an additional deceleration arises from the pre-crash safety systems, such as Advanced Emergency Braking System (AEBS). By utilizing this model across a spectrum of reasonably foreseeable scenarios, a concrete preventable boundary can be derived as a safety evaluation criteria applicable for ALKS limited to less than 60 [km/h] and highway domain (Fig. 10)(4).

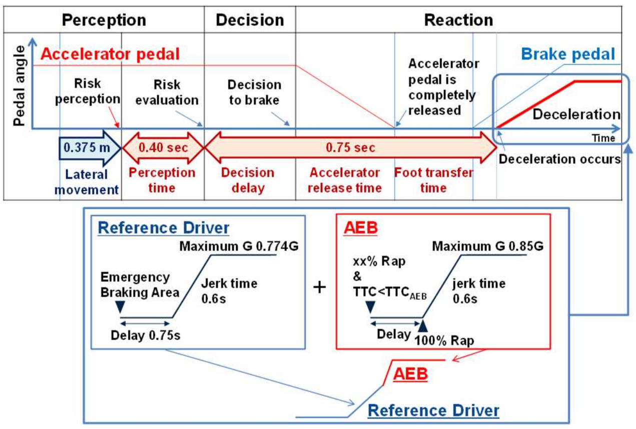


Fig. 9 Human driver behavior model surrogating a competent and careful driver performance

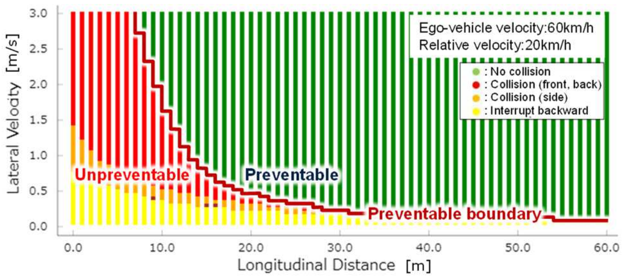


Fig. 10 Example of reasonably foreseeable test scenarios with preventable boundary

This criterion offers the capability to differentiate between the scenario "no collision" and alternative outcomes, relying on computed data to showcase the minimum safety performance requirement for ADS. Furthermore, JAMA (Japan Automobile Manufacturers Association) published a safety evaluation framework for ADS that explains process guided by physical principles. This framework delineates how to formulate and define distinct preventable boundaries, particularly concerning the responder role(14).

4.2.2 Driver behavior model for initiator role (Experiment 2)

1) Approach to define a careless and poor human driver

Fig. 11 illustrates analytical procedures employed to define a careless and subpar human driver behavior based on experiment data. The relationship between a driver's reaction time and their average deceleration rate is scrutinized, utilizing a comprehensive dataset comprising of 152 observations obtained from Experiment 2. Given that the experiment data are generally composed of a spectrum of performances spanning from superior to ordinary and inferior levels, it is effective to define a careless and poor human driver behavior model by statistical processing. In this study, inferior driver performances are extracted on the basis of the bottom 5 percentile values for each relevant indicator. The extracted dataset in this manner constitutes the inferior driver group, as it encapsulates instances of both delayed reaction times and inadequate deceleration rate. Finally, parameter estimation for the model of inferior driver behavior is achieved by processing the representative values derived from the extracted dataset.

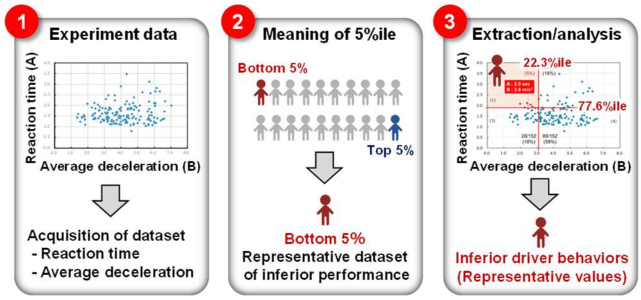


Fig. 11 Processes to define a inferior human driver behavior

Fig. 12 visually presents the correlation between driver reaction time and average deceleration rate. The distribution of drivers' reaction time spans from 0.80 [sec] to 2.82 [sec] and drivers' average deceleration rate are distributed from 1.4 [m/s^2] to 7.1 [m/s^2]. These dataset are analyzed to define inferior driver behavior through the analysis processes described in Fig. 11.

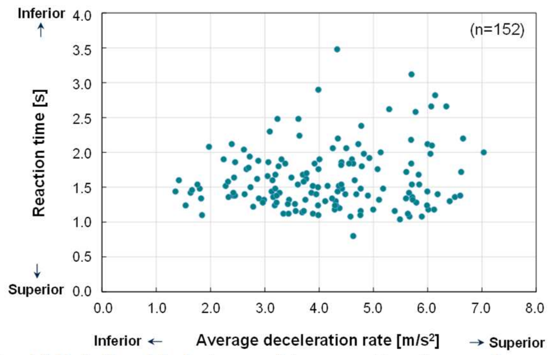


Fig. 12 Relationship between driver reaction time and average deceleration rate (n=152)

2) Analysis of reaction time and average deceleration rate

The distributions of driver reaction time and average deceleration rate are depicted individually in Fig. 13. To identify the inferior driver dataset, two specific values are carefully selected, taking into account the characteristics of each distribution determined, while considering each distribution characteristic to extract the bottom 5 percentile dataset. Recognizing that delayed reactions and diminished deceleration rates signify inferior performance in terms of collision avoidance, the 77.6 percentile value (1.88 [sec]) of reaction time and 22.3 percentile value (3.1 [m/s^2]) of deceleration rate seem to be effective extraction criteria.

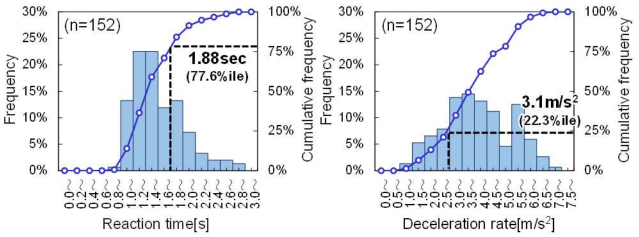


Fig. 13 Distribution of drivers reaction time and average deceleration rates

Fig. 14 presents a visual representation of the classified driver performance groups, alongside a comparison of the final time-headway observed within each group. Group (1) (n=7), exhibits characteristics indicative of both delayed reaction and inadequate deceleration. Conversely, Group (2) (n=28) and (3) (n=28) are composed of drivers who demonstrate either late reaction or poor deceleration, respectively. Importantly, Group (4) (n=89) does not meet the criteria for being categorized as an inferior driver behavior dataset, as neither of the aforementioned features applies to this group. Upon the successful extraction of an appropriate dataset for the inferior driver behavior model, the representative values (reaction time : 2.0[sec], average deceleration rate : 2.6[m/s^2]) of group (1) can be concrete parameters surrogating driver's late reaction and poor brake operation.

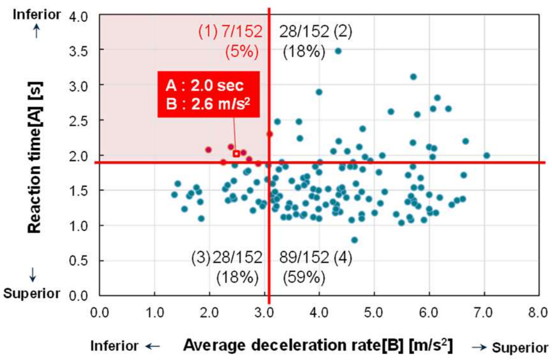


Fig. 14 Classification result of 4 groups based on driver's performance (reaction time and deceleration rate)

3) Analysis of driver's desired minimum time-headway

As illustrated in Fig. 15, the component rate of driver reactions in response to different THW values (0.150-1.125[sec]). Notably, at least 20[%] drivers tend to engage in brake operation with a deceleration exceeding 1.5 [m/s^2] when THW is less than 0.9[sec].

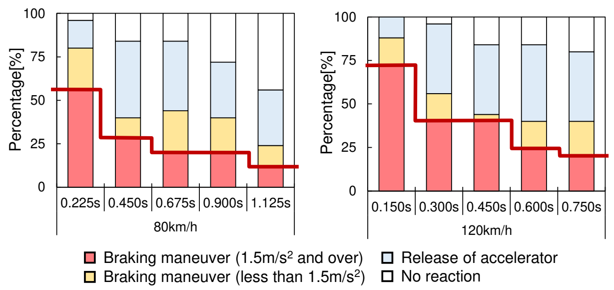


Fig. 15 Component rate of driver reaction toward different time-headway values

Although it is difficult to identify a value universally acceptable and accommodating for all drivers, including those who do not apply the brake operation. Drivers generally expect a minimum THW of more than 1.0[sec] following the completion of a cut-in maneuver by another vehicle in front of the rear vehicle.

4) Safety criteria to prevent interference for rear vehicle

Three parameters are determined through analysis of experiment data. Fig. 16 depicts a specific model of safety criteria to prevent interference. For surrogating inferior driver behavior, reaction time is set to 2.0[sec], deceleration rate is set to 2.6[m/s^2], and minimum final gap time is set to 1.0[sec].

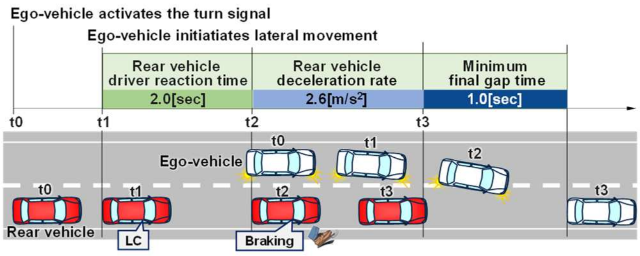


Fig. 16 Parameters of driver behavior model of rear vehicle

This driver behavior model of rear vehicle allows for the delineation of a boundary to distinguish permission area from prohibition area when ADS attempts a lane change (Fig. 17). For instance, consider an ADS operating at 60[km/h] attempting a lane change ahead of a rear vehicle travelling at 120[km/h]. In this scenario, a relative distance is required more than 103[m] (idle running distance of 33[m], stopping distance of 53[m], minimum headway distance of 17[m]) to prevent interference for the surrounding driver. Thus, this methodology offers a valuable approach to defining quantitative safety criteria for the initiator role of ADS, which must ensure not only collision avoidance but also interference prevention in its role as an initiator.

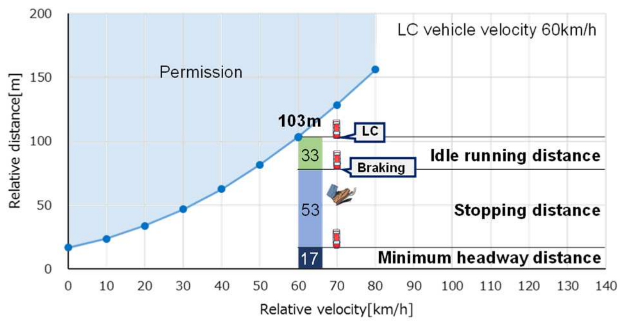


Fig. 17 Example of calculated distance as preventable boundary to assure sufficient margin for rear vehicle

5) Consideration using real traffic data

Merely defining a safety criteria based on experiment data or previous research findings is insufficient. It is crucial to assess whether the proposed criteria align with real-world lane change events. As depicted in Fig. 18, a comparison is presented between the proposed safety criteria and actual instances of lane change. When relative velocity exceeds 10[km/h], the proposed safety criteria can be compatible to almost all actual lane change events. Conversely, with relative velocities below 10[km/h], human drivers tends to initiate lane changes at closer position distances than prescribed by the proposed safety criteria. The mentioned characteristic underscores a complex facet of interaction among human drivers. Specifically, the driver of the leading vehicle tends to anticipate that the driver of the rear vehicle is more receptive to lane changes at closer distances when the velocity is below 10 [km/h]. Given that this aspect raises a pertinent concern for the proposed safety criteria, it becomes essential to investigate and examine this issue continuously, based on various evidences such as experimental data and real-world traffic data.

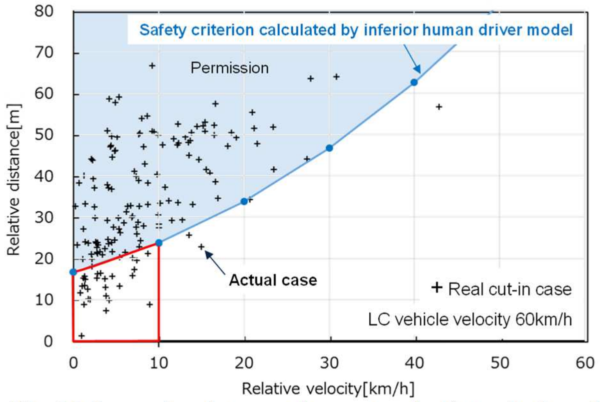


Fig. 18 Comparison between the proposed safety criteria and actual lane change cases

4.3 Argument points to define socially acceptable safety criteria

This paper proposed an approach to define a preventable boundary for two distinct aspects (responder/initiator), achieved by contrasting with human driver behavior. However, this approach has several technical issues that necessitate resolution to establish more universally acceptable safety criteria as in the following.

1) Continuous refinement of way to define preventable boundary

It is necessary to continuously survey related research papers and trends pertaining to international standards and regulations is essential, as relying solely on the comparison with human driver behavior may not be best way to define preventable boundaries. Furthermore, although there may not exist one boundary to compart with real-world traffic completely, identifying a reasonable level that caters to the diverse needs of various stakeholders emerges as a prominent medium and long term concern.

2) Quantifying qualitative statements of related laws

In this study, our endeavor revolved around the qualification of interference from the perspective of the rear vehicle driver. We achieved this by leveraging experiment data and real traffic data. There are still various qualitative statements not only about drivers but also vulnerable road users in at least Japanese Road Traffic Act. As a result, many researches are required to conduct systematically for quantifying these qualitative statements related to the establishment of a preventable boundary.

3) Definition of preventable boundary for vulnerable road users

The current ODD of ADS is undergoing a transition from highway to urban domains. This shift is prompted by the likelihood of ADS encountering pedestrians or cyclists in urban settings. it is need to extend defining Consequently, there arises a necessity to expand the definition of a preventable boundary that is applicable to vulnerable road users. in order to execute safety evaluation. This extension is essential to enable safety evaluations that encompass scenarios involving vulnerable road users. This viewpoint is pivotal for achieving the realization of a safer ADS.

5. Conclusion

In conclusion, this research introduces a novel concept of driver behavior modelling to establish a preventable boundary , achieved through a comprehensive comparison with human driver behavior. The proposed concept facilitates the derivation of a specific human driver behavior model, accomplished by dissecting driver maneuvers into detailed processes and subsequently parameterizing them based on relevant empirical evidence. Furthermore, this approach empowers the definition of preventability, adaptable to the varying aspects of ADS, aligned with the dynamics of safety evaluation scenarios.

Future endeavors encompass the enhancement and refinement of this conceptual framework, which involves the advancement of modeling methodologies and the continuous updating of parameters as well as to apply to definition of preventable boundary toward vulnerable road users assuming safety evaluation in urban domain.

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