Effects of a Driver Assistance System with Foresighted Deceleration Control on the Driving Performance of Elderly and Younger Drivers

Yuichi Saito[a,b,*], Ryoma Yoshimi[b], Shinichi Kume[b], Masahiro Imai[b], Akito Yamasaki[c], Takuma Ito[d], Shintaro Inoue[e], Tsukasa Shimizu[f], Masao Nagai[g], Hideo Inoue[h], Pongsathorn Raksincharoensak[b]

[a] *University of Tsukuba, Tsukuba, Ibaraki, 305-8573, Japan*
[b] *Tokyo University of Agriculture and Technology, Koganei, Tokyo, 184-8588, Japan*
[c] *Meijo University, Nagoya, Aichi, 468-8502, Japan*
[d] *The University of Tokyo, Bunkyo, Tokyo, 113-8656, Japan*
[e] *Toyota Motor Corporation, Susono, Shizuoka, 410-1193, Japan*
[f] *Toyota Central R&D Labs, Nagakute, Aichi, 480-1192, Japan*
[g] *Japan Automobile Research Institute, Tsukuba, Ibaraki, 305-0822, Japan*
[h] *Kanagawa Institute of Technology, Atsugi, Kanagawa, 243-0292, Japan*

Abstract

It is imperative to enhance the safety of elderly individuals on the roads to ensure the quality of their daily life. Near-miss incidents or accidents at blind intersections often result from a conflict between the behaviors of the driver and of other road users (pedestrians and cyclists). The failure to search for potential conflict in the context of blind intersections is a concern pertaining to road safety. The proposed assistance system performs a proactive braking intervention to achieve a referenced velocity in uncertain situations, such as one in which an unobserved pedestrian might initiate a road crossing. The proactive braking intervention attempts to manage the potential risk of crashing with respect to covert hazards. Because an automated system may impair a human's ability to perceive and respond to hazardous situations while driving, this study was designed to examine the effects of proactive braking intervention and visual support cues on elderly and younger drivers' ability to respond to information about potentially hazardous situations. We conducted a public-road driving experiment involving 108 elderly and younger drivers from two non-overlapping age groups. It was observed that the vehicle slowdown realized through the proactive braking intervention enabled the drivers to perform safety confirmation near blind spots and caused them to be more sensitive to and wary of potential hazards. This approach could be effective not only for elderly drivers, but also for young or inexperienced ones.

Keywords: Safety, advanced driver-assistance systems, driving performance, foresighted driving, hazard, elderly drivers

*I am corresponding author
Email address: saito.yuichi.gt@u.tsukuba.ac.jp (Yuichi Saito)

1. Introduction

Pedestrians and vehicles share common road spaces [1]. Crossing a road is risky for pedestrians, and one of the most common types of fatal traffic accidents (35.2%) involves people walking on the side of a road [2]. Speed is a major factor in the lethality of these collisions: mortality rates increase sharply when the collision velocity is greater than 30 km/h [3]. Age is also a factor: elderly people often feature in such accidents, either as pedestrians or drivers. In 2019, 55.4% of all traffic accident fatalities in Japan involved people aged 65 years or more [2]. To reduce the high incidence of traffic accident fatalities among the elderly, approaches must be developed that consider both the age-related functional limitations of elderly drivers [4, 5, 6] and the frailty of elderly pedestrians.

Proactive safety technologies have undergone rapid development in the past decade [7, 8, 9, 10, 11]. Advanced driver assistance systems (ADAS) have been developed that can enhance perception, arouse attention, set off warnings, and perform automatic safety control [12, 13], depending on the driving situation. Some researchers have proposed ADAS that can compensate for the reduced driving performance of elderly drivers [14, 15, 16] by assisting with perception, situation recognition, and action selection. Davidse [17] focused on drawing driver attention to approaching traffic, detecting objects located in blind spots, and ensuring that drivers have a suitable knowledge-base for handling future traffic situations. Although the providing information could be useful for elderly, it might not be sufficient to ensure the driving safety. In an investigation regarding the reaction time and rear-end collision warnings among elderly drivers [18], it was noted that approximately 30% of the participants could not execute evasive behavior to avoid a crash. In general, because elderly drivers often have a significantly longer reaction times than younger drivers, it is difficult for them to make complex decisions under time constraints.

Since 2005, drive recorders have been used to record real-world near-miss incident data from more than 200 taxi vehicles in the Tokyo, Shizuoka, Kyushu, and Hokkaido regions [19]. Currently, approximately 140,000 such event data are registered in the database system of the Tokyo University of Agriculture and Technology and used to perform human error analysis. It has been found that in certain scenarios, such as when pedestrians or cyclists rapidly appear from blind spots or occlusions, existing autonomous emergency braking functions cannot avoid crashes. Therefore, it is important to predict the "hidden risk" in driving situations and control the vehicle velocity to prepare for any unexpected upcoming hazardous events. When expert drivers are confronted with uncertainty, they naturally seek to reduce it by obtaining more information and attempting to fit their current driving situation into a pre-existing category from their previous experience. Based on the contextual information, e.g., the number of parked vehicles in an urban area, the drivers can estimate the probability of any likely scenario, such as a playing child moving onto the road. When necessary, expert drivers adopt preventive measures, so-called "hazard-anticipatory driving behaviors," such as decreasing their velocity and ensuring that a sufficient braking distance is available in case an unexpected event occurs. This additional braking distance is referred to as the "safety cushion [20]" (Figure 1). With an appropriate safety cushion, the drivers can stop the vehicle with a relatively gradual deceleration.

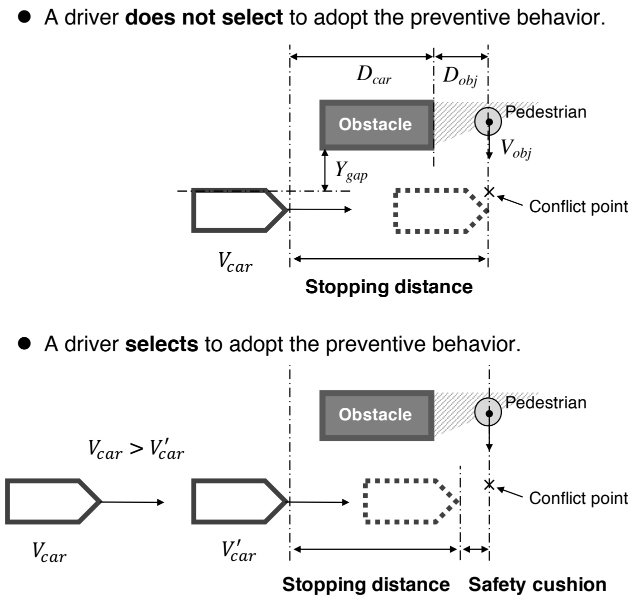

Figure 1: Safety cushion.

An essential question here is how to model foresighted driving behavior. In our research, we define the boundary conditions of a functionally acceptable state of affairs [21]. We assume a scenario in which a pedestrian darts out from a blind area and, in the absence of braking or evasive maneuvers, collides with the front corner of the vehicle on the passenger's side. The reference terminal speed is defined as the maximum velocity at which a collision with the pedestrian is avoidable with the support by an autonomous emergency braking system in critical conditions where obstacles suddenly appear in front [22]. The design parameters for calculating this speed are: 1) the (assumed) pedestrian or cyclist information (i.e., the dart-out speed, V_{obj}, and the spatial distance, D_{obj}, between the pedestrian and the environmental factor creating the blind spot); 2) the evasive-behavior performance (i.e., the recognition time, τ, and maximum achievable deceleration, a_{max}); and 3) the measurable information (i.e., the lateral and longitudinal distances (Y_{gap}, D_{car}) between the subject vehicle and the factor creating the blind spot), as indicated by Figure 1. From these, when the vehicle approaches a blind area, a foresighted driver model calculates the reference terminal speed and the longitudinal deceleration needed to reach it [22]. In previous work, we developed an experimental vehicle with driver-model-oriented driving intelligence to enhance safety in potentially hazardous situations [23]. Rather than rely on the driver to slow down, the driver assistance system [22, 24] can exert deceleration control, the main characteristics of which are as follows:

- The driver remains in primarily command of their driving. When the ADAS determines that the vehicle is approaching an intersection with a blind area, the awareness regarding the blind intersection location is enhanced, with the system providing the auditory and visual support cues on a head-up display (HUD).
- When the ADAS determines that the current vehicle velocity is higher than the ref-

erence terminal velocity, it implements deceleration control, but only for the duration of the potentially hazardous situation.

- The ADAS provides proactive braking intervention based on a machine-initiated strategy. Although the drivers can always implement the braking action, a higher brake pedal stroke among the human driver and the machine is selected; both the human's action and the system's action are coupled in the way that the higher brake command stroke is adopted. On the other hand, the accelerator pedal's action is canceled during this intervention.

A common issue in many of studies of human-machine systems is understanding drivers' interactions with a new ADAS. The ADAS mentioned above is activated in a loop of hazard-anticipatory driving, which requires the separation of the tasks of spotting, comprehending, appraising and/or anticipating, and responding to an on-road hazard. The process of identifying and/or predicting hazardous situations has been widely discussed in theoretical studies pertaining to hazard perception [25] and/or situation awareness [26]. In general, these skills are correlated with traffic accidents, and several researchers have investigated the influence of age and experience on these skills [27, 28, 29, 30]. Normally, the terminal velocity when passing blind intersections reflects the risk tolerance of the driver in responding to on-road hazards, balancing the desired vehicle velocity against the anticipated hazard potential of a specific driving situation. However, under a safety-first policy, our ADAS adopts preventive measures to avoid and/or mitigate the damage that could occur at the occlusion. In the automated driving domain, human factors researchers have investigated reactions to a "take-over request" under various conditions to assess the drivers' take-over performance [31, 32, 33]. In such scenarios, the central concern is that an automated system may impair a human's ability to perceive and respond to hazardous situations while driving. Young & Stanton [34] indicated an increase in brake reaction time of approximately 1 s in scenarios in which a leading vehicle suddenly decelerates when using adaptive cruise control. It has been reported that automated systems can reduce the driver vigilance [26], as the driver looks away from the road for longer periods [35, 36].

The effectiveness of proactive braking-assistance intervention, which modifies the target velocity in the early stages of the response, has been investigated in the literature [22, 24], but only in a driving-simulator environment. Such investigations have limited physical, perceptual, and behavioral fidelity [37]; Käppler [38] has pointed out that the lack of real danger in driving simulators can induce a false sense of safety, responsibility, or competence. Driving experiments with such assistance systems on public roads are sparse. The purpose of the present study is to examine the effects of proactive braking intervention and auditory/visual support cues on the driving performance of both elderly and younger drivers, as measured in actual public-road field tests. The central hypothesis of this work is the following:

- Proactive braking interventions increase safety for elderly and/or inexperienced drivers, not only by guiding the vehicle to the reference terminal velocity, but also by increasing the opportunity (i.e., available time) for a driver to search for hidden dangers in blind spots. The demonstration of reactive behaviors that enhance safety, (in particular, carefully searching in blind spots), would indicate that the participant has been made more aware of potential hazards.

2. Method

The driving experiment was conducted with the approval of the ethics committee of the Tokyo University of Agriculture and Technology.

2.1. Experiment design

A between-subjects design was adopted for the public road experiment. The independent measure was the driving condition. Three conditions were considered: standard: driving without using the functions to support hazard-anticipatory driving; visual support: driving with visual support cues display and auditory alerts; and full support: driving with the complete set of proactive braking intervention, visual support cues, and auditory alerts.

2.2. Apparatus

The experiment was conducted using a vehicle equipped with several sensors (Figure 2) as well as a map platform, developed for our previous work [39], with lean-configuration sensor suites and small-sized digital maps. The main functions of the digital maps were 1) localization: by comparing map data to landmarks (e.g., crosswalks, road-paint marks, and stop lines) detected by the front and rear cameras, the ADAS grasps the vehicle's current position on the map; and 2) long-range sensing: knowing the current position, the ADAS anticipates elements such as blind intersections that lie in front of the vehicle according to the map [39]. In order to realize these functions, we have referred to the existing ADAS Horizon system proposed by the PReVENT project [40]. ADAS Horizon defines a map as the combination of a main path and sub-paths that separate from main path at a node called a "stub." The vehicle position and various associated elements of the traffic environment are defined in terms of their offsets, i.e., the driving distances to them, measured from the origin stub of the main path [39]. The coordinates of elements such as blind intersections were embedded into the digital map. The foresighted driver model calculated the reference terminal velocity at these blind intersections through localization and long-range sensing; the acceleration commands necessary for reaching this velocity could then be input to the digital signal processor if required. Furthermore, a driver monitoring system with a monocular camera was used to investigate the face-pose direction (roll, pitch, and yaw) of the driver. Takano et al. [41] have proposed a method to estimate the face-pose direction and facial parts (i.e., eyes, mouth, nose, eyebrows) from a facial image, matching the image to a 3D shape model of the face. (The model is created using the Point Distribution Mode (PDM) [42], a three-dimensional distribution of facial feature points.) Based on this method, the three-axis face directions were estimated by offline processing with recorded images [43], as shown in Figure 2.

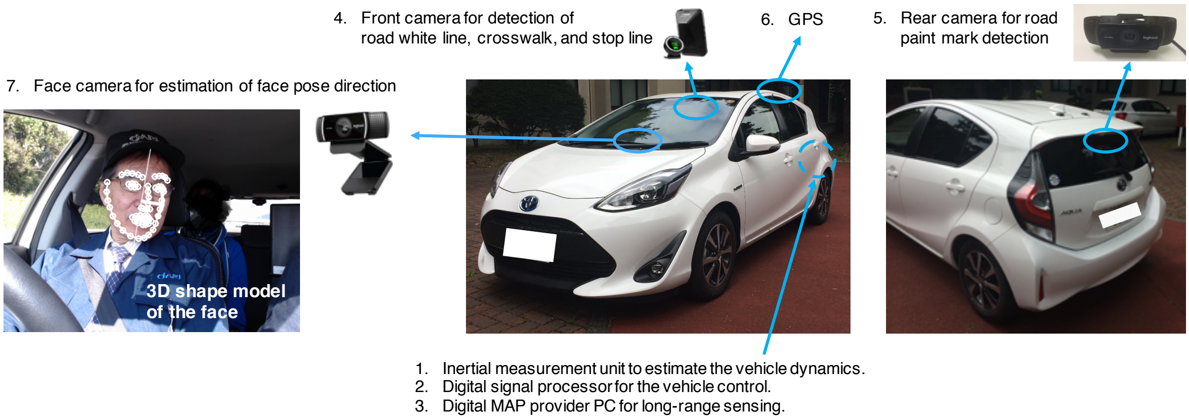

Figure 2: Sensor configuration in the experimental vehicle.

2.3. Functions of the driver assistance system

The driver assistance system has two main functions: providing the driver with information to improve the understanding of potentially hazardous situations, and performing braking intervention to guide the vehicle to the reference terminal velocity. When the ADAS determines that the vehicle is approaching an intersection including blind areas, it calculates the time to intersection (TTI), defined as the time it would takes for the vehicle to reach the blind spot at its current speed. If this is less than 7.5 s, the ADAS informs the driver in a way taken, with slight modifications, from previous studies [44, 45, 46]: the driver is presented with a visual support icon, as shown in Figure 3 (a), and an auditory alert, which provides information about the distance to and visibility of the intersection. Subsequently, when the TTI is less than 5 s, the ADAS enforces deceleration control; the visual support icon is switched to the "slow down" symbol shown in Figure 3 (b), which indicates that the vehicle is decelerating through the intervention. (In visual support condition in our experiment, the same indications, but without deceleration control, were provided as a means of arousing attention. Note that, in Japan, the "slow down" symbol on a traffic sign means to reduce one's speed to 10 km/h or less.) When the vehicle reached a designated end position, deceleration control was terminated, and the visual support icon disappeared. In this case, the end position was set to 1.86 m before the blind spot.

We now briefly describe the pre-determined terminal velocity used in deceleration control. In a previous study [47], we collected natural driving data[1] from professional driving instructors passing a blind intersection mentioned in Sections 2.5 and 2.6. Analyzing the data from 14 runs in which the instructors' driving was not significantly affected by other road-users' behavior, we found that the average velocity when passing the intersection was

[1]We recruited six instructors from a driving school to demonstrate driving with proactive safety in an urban area. We planned a 4 km driving course (in an area containing a station, a high school, apartments and blind intersections) for the experiment. Each driver gave two demonstrations at 9 a.m. and two at 4 p.m. (the two busiest times/rush hours in this area). We collected data for 21 passes through the blind intersection by the expert drivers in this experiment [47].

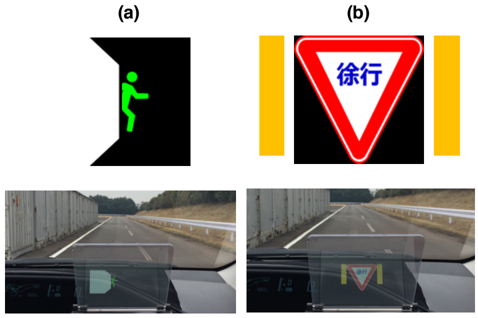

Figure 3: Information reflected on the head-up display (HUD). The triangular shape "slow down" symbol mimicks the standard road traffic sign on public roads. In Japan, the "slow down" symbol means to reduce the vehicle speed to 10 km/h or less.

8.36 km/h. (This was almost exactly the same as the reference terminal speed calculated from the following parameters: V_{obj} = 3 m/s, D_{obj} = 0.5 m, τ = 0.6 s, a_{max} = -6 m/s^2, and Y_{gap} = 1.6 m.) The reference terminal velocity in the present study was accordingly set to 8.36 km/h.

2.4. Participants

Through the services of the Silver Human Resources Center in Koganei City, Tokyo, we recruited 70 participants aged between 65 and 85 years (mean age: 72.6 years, SD: 5.17) who periodically drove and who had corrected visual support acuities of 0.7 or better according to a Landolt-ring vision test. In addition, through the services of Tokyo University of Agriculture and Technology, we recruited 67 participants aged between 22 and 30 years (mean age: 23.6 years, SD: 1.54) who had corrected visual support acuities of 0.7 or better. Every participant had a valid driver's license and drove the experimental vehicle with voluntary insurance that included unlimited bodily injury and property damage coverage on a public road subject to the Road Traffic Act.

2.5. Procedure

All the participants drove on designated public roads in Koganei City. An instructor from the car-manufacturing company sat in the passenger seat of the car. The role of the instructor was not only to guide the participants through the driving course, but also to ensure safety: the instructor could stop the vehicle at any time by using the auxiliary brakes.

The driving course is shown in Figure 4. It was divided into three sections: practice, adaptation, and evaluation, with driving distances of 3, 4, and 2.5 km, respectively. The practice and adaptation sections were designed to let the drivers to familiarize themselves with the experimental vehicle and to construct a mental model of the system's operation, respectively. The evaluation section was designed to assess driver behavior. The total driving time was approximately 47 min, excluding the break time between sections. The participants did not receive any clarification regarding the distinction between the adaptation and evaluation sections.

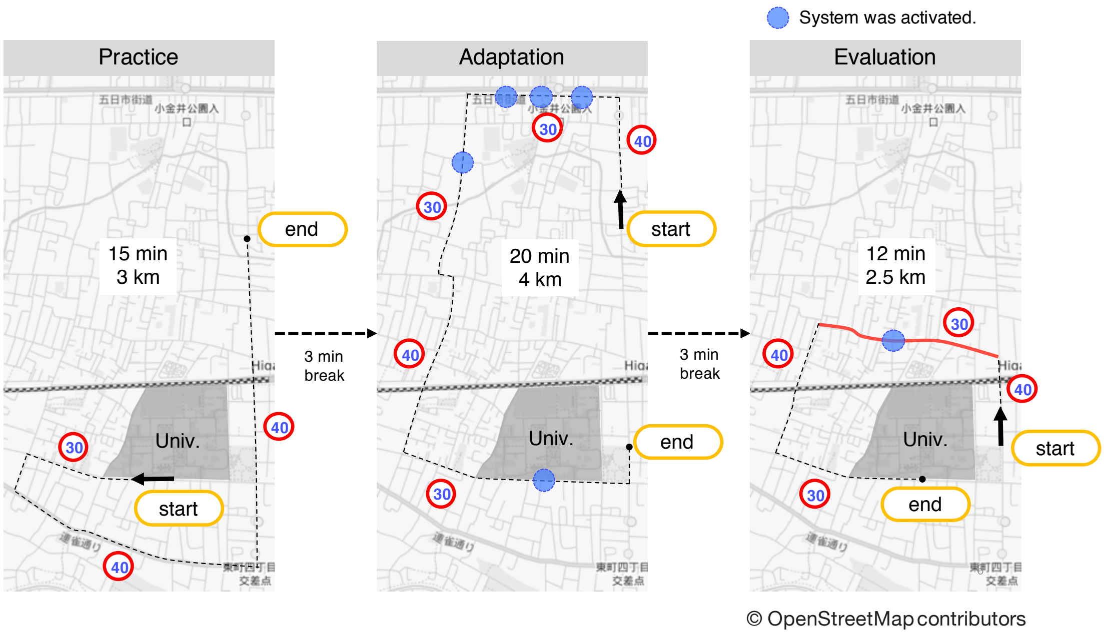

Figure 4: Description on the driving course.

The main focus of the research was how the participants would behave as they approached blind intersections along the route. The blue circles in Figure 4 were intersections with poor visibility. At those intersections, mirrors were present to extend a driver's field of view, which was limited by barriers such as the building's wall and fence. (Figure 5). In general, drivers can make good use of their mirrors when passing through the intersection at low speeds. Most of the participants did not have any prior experience with the driving course.

Data for four participants were recorded each day. The experiment was divided into morning and afternoon sessions, with each session including two participants. Each participant first read and signed a written consent form and answered a pre-questionnaire. The questionnaire survey included i) a trail-making test (TMT) [48, 49] to examine the subject's attention function, and ii) a Mini-Mental State Examination (MMSE), which has been used widely for screening dementia. (We confirmed that none of the participants showed evidence of dementia.) After receiving written instructions pertaining to the purpose, method, and procedure of the experiment, in the practice section, the participants were instructed to drive as usual and to comply with the Road Traffic Act. Under visual support and full support conditions, the participants were also given an instruction regarding essential aspects of the ADAS interface, after which the angle of the HUD, the brightness of the icons, and the volume of the auditory alert were adjusted for each participant so that they were able to recognize ADAS interface. In visual support and full support conditions, the participants were required to drive while taking advantage of the assistance features. After the instructions, the participants drove first along the practice section, then along the adaptation section, and finally along the evaluation section. After each of these three drives, a three-minute break was provided. Next, the participants answered the acceptance questionnaire developed by Van der Laan et al. [50], indicating their opinions regarding the ADAS on a total

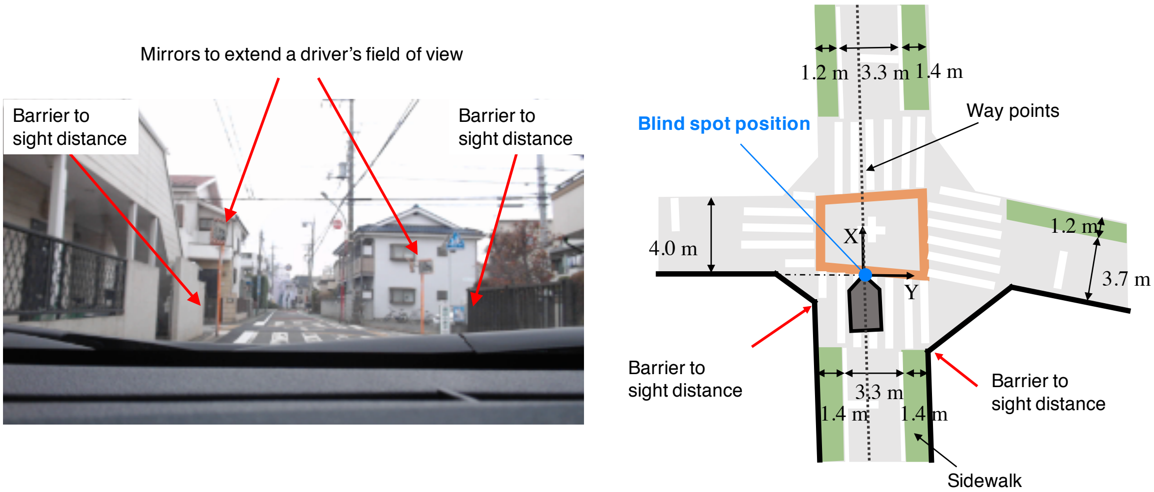

Figure 5: Description on the test scenario (blind intersection).

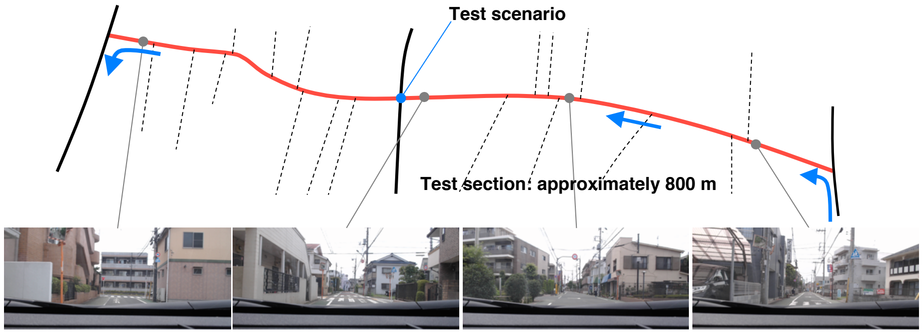

Figure 6: Description on the test section (approximately 800 m).

of nine items (useful, good, effective, assistive, raises alertness, pleasant, nice, likable, and desirable) using a five-point rating scale. Finally, a post-questionnaire survey pertaining to their impressions of the ADAS was administered; the participants answered the questions using a six-point rating scale. The total duration of the experiment was approximately three hours for the morning and afternoon sessions, respectively.

2.6. Dependent Measures

During the experiment, the following parameters were measured at a frequency of 100 Hz: driving distance [m]; speed [km/h]; longitudinal acceleration [m/s^2]; desired acceleration [m/s^2]; remaining distance to the intersection based on the estimated vehicle current position [m]; accelerator pedal ratio [%]; information pertaining to brake operation [0: the driver is not pressing the brake pedal, 1: the driver is pressing the brake pedal]; and the time and/or distance at which the deceleration control was initiated [s]. Facial images were collected at 10 frames per second. In both test scenario and test section of Figures 6 and 5, the driver's behaviors were evaluated. The blind spot position (982.61 m) was defined as the position at which the driver's field of view was again unrestricted. In the test scenario, the data for the 100 m interval ($\in [912.6, 1012.6]$) around the intersection were automatically extracted. In the test section, the data for the approximately 800 m interval ($\in [533.1, 1311.8]$) were also extracted. The following dependent variables were calculated for every drive for each participant:

- Whether or not a braking action was performed in the 100 m interval.
- Accelerator release time (ART) [s], that is, the TTI when the accelerator pedal was released. (Whether or not the accelerator was released prior to the initiation of deceleration control was also investigated.)
- Accelerator onset position (AOP) [m], that is, the vehicle position when the accelerator pedal was depressed. (A negative or positive value means that the accelerator action was carried out before or after reaching the blind spot position, respectively. Whether or not the accelerator action was initiated after the end of deceleration control was also investigated.)
- Terminal velocity (TV) at the blind spot position [km/h]. (In full support condition, the vehicle was guided to the reference terminal velocity, whereas in standard and visual support conditions, the terminal velocity was unrestricted and thus chosen by the driver.)
- Maximum value of the estimated collision velocity (MCV) [km/h] [51]. (It is rare for drivers to encounter a situation in which an "invisible" object crosses the road. Meanwhile, the damage resulting from the event is obviously unacceptable. We assumed that a virtual cyclist attempted to cross the road at each sampling time in the interval ($\in [912.6, 982.6]$). The velocity of the virtual cyclist was set as 3 m/s. The driver assistance system was expected to realize autonomous emergency braking (reaction time = 0.6 s and average acceleration = -6 m/s^2) if the possibility of a collision was identified. The maximum value of collision velocity calculated at every sampling time was evaluated by using the recorded time-series data, which can be interpreted as an objective index of potential risks.)
- Eighty-fifth percentile of the velocities recorded in the test section (85V) [km/h]. The driving context consisted of an urban area with a one lane two-way road with a road width of 3.3 m and a legal speed of 30 km/h. Cyclists and pedestrians were occasionally present. This reflected the driver's how sensitivity to and wariness of potential hazards.
- Maximum face yaw angle (MFYA) near the blind spot position [degrees]. (This value reflected how far the participant looked while responding to the potentially hazardous situation.)

- Standard deviation of the face yaw angle (SDFYA) recorded in the test section [degrees]. (This reflects how much the participant looked about for potential hazards.)

2.7. Statistical Analysis

The experiment was conducted as a 2 × 3 between-subjects design (i.e., two age groups and three driving conditions). The data from 108 of the 137 participants were used in this analysis. We excluded 21 runs in which actual cyclists or pedestrians were present in the 100 m interval, because we wished to focus exclusively on analyzing how driver behavior was affected by the occlusion rather than by visible road users. In addition, eight runs in which the driver action of releasing the accelerator was not observed in the 100 m interval, suggesting that the driver did not intend to decelerate, were excluded from the analysis. Among the elderly participants, this happened twice in standard condition and once each in visual support and full support conditions; among the younger participants, it was never observed in standard condition, but happened twice each in visual support and full support conditions. After these were excluded, we had data from 20, 19, and 18 elderly participants and 18, 18, and 15 younger participants driving in standard, visual support, and full support conditions, respectively.

The first stage of the study specified and described the differences between elderly and younger drivers. We collected drivers' ages [years], driving experience [years], driving distance per year [km], scores on TMT-A [s] and TMT-B [s], delta TMT [s], and MMSE [pt]. (Delta TMT is the difference between the TMT-B and TMT-A scores; it is often used as a measure of cognitive flexibility [48, 49].) Descriptive statistics (means and standard deviations) were calculated, and between-group comparisons were made by independent-sample t-tests. Then, within each age group, between-driving conditions were compared via a one-way analysis of variance (ANOVA).

The second stage of the study examined the effects of proactive braking intervention and visual support cues on driver performance. The dependent variables included ART, AOP, TV, MFYA, 85V, and SDFYA. The MCV was excluded from the statistical analysis, because this indicator was highly correlated with the TV indicator.

First, correlations among the dependent variables were examined to gain understanding of the drivers' interactions with the proposed ADAS. Then, a multivariate analysis of variance (MANOVA) procedure was used to investigate all of the interaction and main effects on these dependent variables due to the two factors. For this analysis, SPSS (Statistical Package for Social Science) was used. We found significant results for Box's test ($F_{105,15767.24} = 1.64$, $p < 0.001$) and Levene's test ($F_{5,102} = 8.96$, $p < 0.001$) for the TV indicator. Thus, the assumption of homogeneous variance-covariance matrices was rejected. Consequently, we set alpha levels at $p < 0.01$ for interpreting significant results in the MANOVA procedure. Given the significance of the overall test, the univariate two-way ANOVA was examined for these variables. For the TV indicator, pairwise comparisons were examined using Tamhane's T2. For the remaining indicators, pairwise comparisons were examined using Tukey's test. In addition, for the question of whether or not the braking action was performed, Fisher's exact test of independence was used, and pairwise comparisons were examined using Holm's method.

Table 1: Descriptive values of the number of drivers, their ages [years], driving experience [years], driving distance per year [km], scores on TMT-A [s] and TMT-B [s], delta TMT [s], and MMSE [pt]

Group	Condition	N	Age M (SD)	Experience M (SD)	Distance M (SD)	TMT A M (SD)	TMT B M (SD)	Delta TMT M (SD)	MMSE M (SD)
Elderly	standard	20	70.2 (4.9)	46.9 (8.6)	4205 (4729)	84.7 (33.0)	114.0 (42.9)	29.2 (23.2)	28.4 (1.5)
	visual support	19	76.5 (4.4)	50.7 (7.3)	3436 (4384)	101.6 (28.8)	131.5 (53.2)	29.8 (36.3)	27.9 (2.2)
	full support	18	71.0 (4.0)	44.4 (10.1)	5611 (4013)	92.7 (35.0)	104.7 (36.8)	11.9 (17.6)	28.7 (1.6)
	all	57	72.5 (5.2)	47.4 (8.9)	4392 (4410)	92.9 (32.5)	116.9 (45.5)	23.9 (27.7)	28.3 (1.8)
Younger	standard	18	22.8 (0.9)	3.7 (1.4)	1806 (2757)	55.3 (12.1)	57.1 (16.4)	1.7 (15.6)	29.3 (1.1)
	visual support	18	23.6 (1.0)	4.1 (0.9)	2445 (5969)	51.7 (8.9)	58.8 (9.5)	7.0 (9.6)	29.6 (0.5)
	full support	15	24.7 (2.4)	4.7 (1.8)	1160 (1253)	50.0 (13.0)	55.9 (13.4)	5.8 (9.9)	29.6 (0.7)
	all	51	23.6 (1.7)	4.1 (1.4)	1853 (3976)	52.5 (11.3)	57.4 (13.1)	4.9 (12.1)	29.5 (0.8)

Note: Trail making test (TMT), Mini-Mental State Examination (MMSE).

3. Results

Table 1 gives the means and standard deviations of the driver data collected in the first part of the study. The independent-sample t-tests comparing age groups revealed significant differences in the age ($t(107) = 63.88$, $p < 0.05$, $d = 12.25$), driving experience ($t(107) = 34.34$, $p < 0.05$, $d = 6.59$), driving distance ($t(107) = 3.14$, $p < 0.05$, $d = 0.60$), TMT-A ($t(107) = 8.49$, $p < 0.05$, $d = 1.63$), TMT-B ($t(107) = 9.08$, $p < 0.05$, $d = 1.74$), delta TMT ($t(107) = 4.57$, $p < 0.05$, $d = 0.88$), and MMSE ($t(107) = 4.28$, $p < 0.05$, $d = 0.82$). For the younger and elderly drivers, respectively, the one-way ANOVA pertaining to the three driving conditions revealed no significant differences in driving experience, driving distance, scores on TMT-A and TMT-B, delta TMT, and MMSE; nevertheless, the effect of age on the driving condition was significant (Elderly: $F_{2,54} = 11.00$, $p < 0.05$, Partial $\eta^2 = 0.29$, Younger: $F_{2,49} = 6.15$, $p < 0.05$, Partial $\eta^2 = 0.20$).

3.1. Effects of ADAS on driving behavior

The statistical descriptions of driving behavior are listed in Table 2. Table 3 shows the results of correlational analyses between dependent variables due to the two factors. Out of a total of 90 correlations, 18 were significant ($p < 0.05$). The main correlations were between TV and MYFA, and TV and AOP. In general, as the terminal velocity decreases, the opportunity for drivers to search for blind spots can be increased. The number of elderly participants who performed the braking action in the 100 m interval around the intersection entry was 18, 17, and 12 in standard, visual support, and full support conditions, respectively; Fisher's exact test of independence indicated no significance ($p = 0.12$). In full support condition, the brake pedal was depressed by 12 out of 18 elderly participants (66 %), and the Pearson correlation coefficient between TV and MYFA was -0.49. This means that, as drivers intentionally further decreased their terminal velocities, their maximum face yaw angle around the blind intersection tended to increase. In addition, as the MFYA became larger, so too did the AOP ($r = 0.47$). By contrast, 14, 14, and 5 younger participants depressed the brake pedal in standard, visual support, and full support conditions, respectively. The result of Fisher's exact test of independence indicated statistical significance ($p = 0.01$, Cramer's $V = 0.42$), and pairwise comparison indicated significant differences

Table 2: Descriptive statistical values for driving indicators.

Driving condition		Elderly						
		ART	AOP	TV	MCV	85V	MFYA	SDFYA
standard	Mean	3.83	-1.71	17.21	12.83	29.63	22.79	7.79
	SD	(1.63)	(7.59)	(8.22)	(10.43)	(3.42)	(15.70)	(3.25)
visual support	Mean	4.09	-0.96	13.37	6.31	27.72	21.97	7.25
	SD	(2.11)	(5.90)	(4.77)	(6.78)	(2.12)	(11.12)	(2.48)
full support	Mean	4.30	-4.67	9.02	0.00	27.21	29.03	8.36
	SD	(2.41)	(11.34)	(2.13)	(0.00)	(2.64)	(17.15)	(1.95)
all	Mean	4.06	-2.39	13.34	6.60	28.23	24.49	7.79
	SD	(2.03)	(8.50)	(6.55)	(8.92)	(2.94)	(14.92)	(2.63)
Driving condition		Younger						
		ART	AOP	TV	MCV	85V	MFYA	SDFYA
standard	Mean	4.13	-5.33	18.25	13.80	30.34	15.35	6.03
	SD	(2.17)	(11.36)	(7.84)	(10.08)	(2.73)	(13.31)	(1.47)
visual support	Mean	4.86	-3.75	19.64	16.00	30.31	15.28	5.44
	SD	(1.91)	(9.16)	(6.23)	(7.95)	(2.84)	(12.92)	(2.09)
full support	Mean	5.49	-6.50	9.78	0.00	27.52	29.97	7.37
	SD	(2.01)	(14.56)	(1.45)	(0.00)	(3.01)	(12.80)	(3.59)
all	Mean	4.79	-5.11	16.25	10.52	29.5	19.62	6.22
	SD	(2.07)	(11.53)	(7.27)	(10.19)	(3.08)	(14.43)	(2.54)

Note: Accelerator release time (ART), accelerator onset time (AOP), terminal velocity (TV), maximum of collision velocity (MCV), 85%tile of velocity (85V), maximum of face yaw angle (MFYA), SD of face yaw angle (SDFYA).

between standard and full support conditions and visual support and full support conditions. This means that the younger participants placed more reliance than the elderly ones in the operation of the deceleration control. In full support condition, only 5 of 15 younger participants (33 %) depressed the brake pedal. As can be seen in Table 2, the standard deviation of the younger participants' TV was smaller than that of the elderly participants under full support condition (SD = 1.45 vs. 2.13). Due to the small standard deviation of the younger participants' TV, correlations between TV and MYFA, and TV and AOP were not observed. On the other hand, interestingly, these correlations were observed in visual support condition with younger drivers. These results show the impact of individual differences in responding to information about a blind intersection. However, these correlations were not significant for elderly drivers. The mean difference in TV indicator was 6.27 under visual support condition (M = 13.37 vs. 19.64, SD = 4.77 vs. 6.23). This suggests that the impact of individual differences may be greater for younger participants than for elderly participants under visual support condition.

MANOVA results revealed a significant effect of the driving condition (Wilks' $\lambda = 0.58$, $F_{12,194} = 4.96$, $p < 0.001$, Partial $\eta^2 = 0.23$). There were no significant main effect of the age group (Wilks' $\lambda = 0.84$, $F_{6,97} = 2.88$, $p = 0.013$, Partial $\eta^2 = 0.15$) and no interaction effect of the driving condition and age group (Wilks' $\lambda = 0.90$, $F_{12,194} = 0.84$, $p = 0.61$, Partial η^2 = 0.05). Given the significance of the overall test, univariate main effects were examined, as shown in Table 4. Significant univariate main effects of the driving condition were observed for the TV, 85V, and MFYA indicators ($p < 0.01$). Pairwise comparisons between the driving condition are shown in Table 5. The results indicate significant differences between standard and full support conditions and visual support and full support conditions ($p < 0.01$) for

Table 3: Pearson correlation coefficients between dependent variables

			standard			
Elderly	ART	AOP	TV	85V	MFYA	SDFYA
ART	–	-0.38	0.14	0.009	0.15	**0.56****
AOP		–	**-0.51***	-0.39	0.34	-0.09
TV			–	**0.57****	-0.32	-0.01
85V				–	-0.08	-0.07
MFYA					–	**0.57****
SDFYA						–
Younger	ART	AOP	TV	85V	MFYA	SDFYA
ART	–	-0.33	0.27	-0.07	**-0.58***	0.17
AOP		–	**-0.50***	0.13	0.41	0.27
TV			–	0.42	-0.45	0.03
85V				–	-0.009	-0.09
MFYA					–	0.02
SDFYA						–
			visual support			
Elderly	ART	AOP	TV	85V	MFYA	SDFYA
ART	–	0.32	-0.04	0.08	-0.29	-0.24
AOP		–	-0.29	-0.11	-0.25	0.01
TV			–	0.28	-0.18	-0.14
85V				–	-0.27	-0.20
MFYA					–	0.44
SDFYA						–
Younger	ART	AOP	TV	85V	MFYA	SDFYA
ART	–	-0.008	-0.31	0.11	0.21	-0.04
AOP		–	**-0.62****	**-0.56***	0.36	0.38
TV			–	**0.50***	**-0.53***	**-0.58***
85V				–	**-0.59****	**-0.49***
MFYA					–	0.27
SDFYA						–
			full support			
Elderly	ART	AOP	TV	85V	MFYA	SDFYA
ART	–	**-0.61****	0.34	**-0.54***	-0.4	-0.26
AOP		–	**-0.75****	0.07	**0.47***	0.09
TV			–	0.12	**-0.49***	-0.04
85V				–	0.003	-0.02
MFYA					–	0.31
SDFYA						–
Younger	ART	AOP	TV	85V	MFYA	SDFYA
ART	–	-0.39	0.21	0.33	-0.25	-0.10
AOP		–	-0.20	-0.27	-0.33	-0.08
TV			–	0.16	0.05	0.30
85V				–	-0.13	-0.42
MFYA					–	0.22
SDFYA						–

** $p < .01$.
* $p < .05$.

Table 4: The results of univariate analysis of variance for driving indicators.

		df	*F*	*p*	Partial η^2
ART	Age group	1, 102	3.61	0.06	0.03
	Driving condition	2, 102	1.74	0.18	0.03
	Age group * Driving condition	2, 102	0.40	0.66	0.008
AOP	Age group	1, 102	1.96	0.16	0.02
	Driving condition	2, 102	0.89	0.41	0.02
	Age group * Driving condition	2, 102	0.06	0.93	0.001
TV	Age group	1, 102	5.62	0.02	0.05
	Driving condition	2, 102	20.15	< **0.001**	0.28
	Age group * Driving condition	2, 102	2.54	0.08	0.05
85V	Age group	1, 102	4.82	0.03	0.03
	Driving condition	2, 102	7.64	**0.001**	0.12
	Age group * Driving condition	2, 102	1.66	0.19	0.03
MFYA	Age group	1, 102	2.63	0.10	0.02
	Driving condition	2, 102	6.57	**0.002**	0.11
	Age group * Driving condition	2, 102	0.93	0.39	0.01
SDFYA	Age group	1, 102	9.42	**0.003**	0.08
	Driving condition	2, 102	3.09	0.05	0.05
	Age group * Driving condition	2, 102	0.26	0.76	0.005

Note: We set alpha levels at $p < .01$ for interpreting significant results.

Table 5: The results of multiple comparison for the driving condition.

	Driving condition		Difference	Std. error	*p*	95% CI	
	(I)	(J)	(I-J)			Lower	Upper
TV	standard	full support	8.33	1.33	< **0.001**	5.02	11.64
	visual support	full support	7.05	1.08	< **0.001**	4.35	9.76
	standard	visual support	1.27	1.65	0.83	-2.77	5.32
85V	standard	full support	2.62	0.67	**0.001**	0.61	4.62
	visual support	full support	1.63	0.67	0.05	-0.38	3.64
	standard	visual support	0.98	0.65	0.29	-0.95	2.93
MFYA	standard	full support	-10.19	3.33	**0.008**	-20.13	-0.24
	visual support	full support	-10.74	3.35	**0.005**	-20.74	-0.73
	standard	visual support	0.54	3.23	0.98	-9.10	10.20

Note: We set alpha levels at $p < .01$ for interpreting significant results.

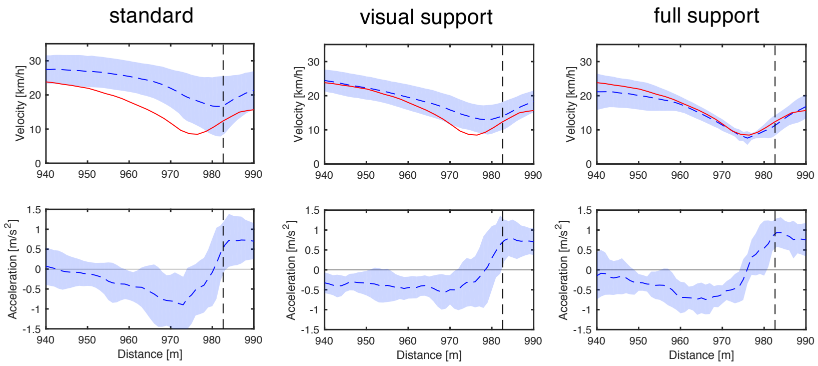

Figure 7: Vehicle longitudinal motion of the elderly drivers. The blue dashed curves represent mean velocity and acceleration; the blue shaded areas represent the corresponding standard deviations. The black-dashed line at 982 [m] indicates the blind spot position beyond which the driver's visual support field was fully restored. The red curve denotes the speed profile (mean) of four driving instructors (over 14 runs), obtained from another experiment around the same intersection [47].

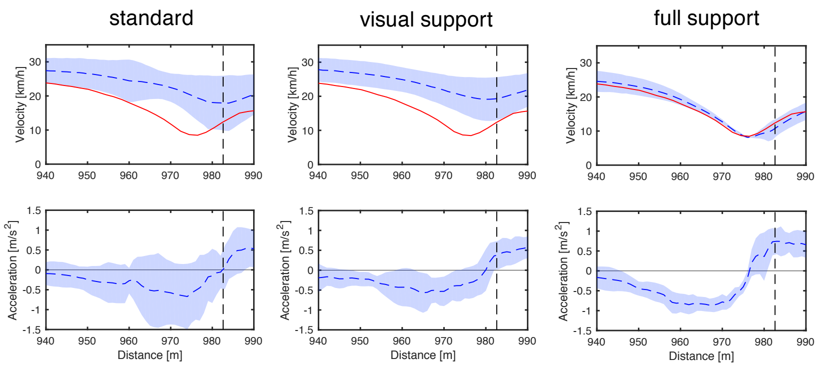

Figure 8: Vehicle longitudinal motion of the young drivers.

the TV and MFYA indicators. For the 85V indicator, a significant difference was observed between the standard and full support conditions ($p < 0.01$). In full support condition, the average TV was lower, and the average MFYA around the blind intersection larger, than in standard and visual support conditions.

For both the ART and AOP indicators, no significant main effect of the driving condition was observed. The accelerator was released prior to the initiation of deceleration control by 6 out of 18 elderly participants (33%) under full support condition. Furthermore, in 14 instances (77%), the accelerator was re-initiated after the end of deceleration control. On the other hand, among younger participants under full support condition, in 7 out of 15 instances (50%), the accelerator was released prior to the initiation of deceleration control, and in 10 instances (66%), it was re-initiated after the end of deceleration control. Because the driver's accelerator input was disabled during the intervention, the vehicle was guided to the reference terminal velocity. As can be seen in Table 2, for both the elderly and younger drivers in full support condition, the MCV was zero, indicating that the collision

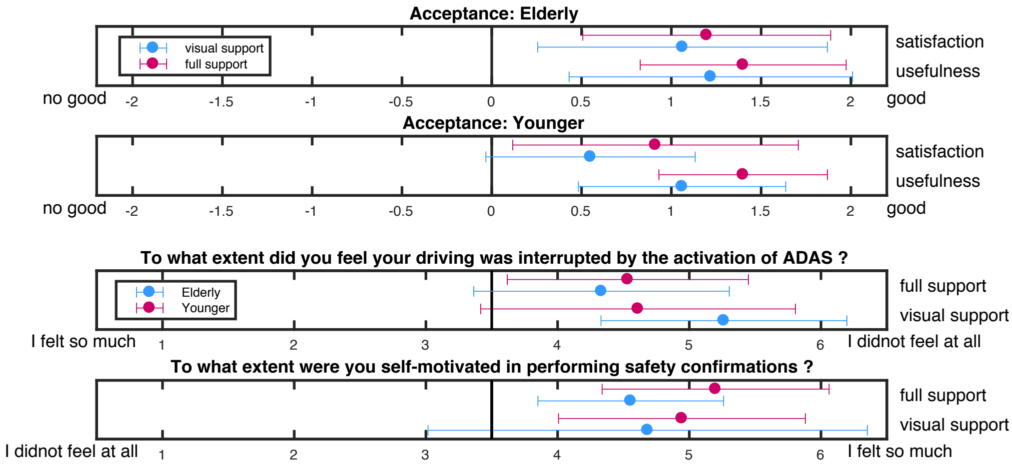

Figure 9: Results of the questionnaire survey.

with the virtual cyclist could be avoided if the autonomous emergency braking was activated. Thus, a decreased potential risk was observed for drivers of all ages in full support condition compared to those in standard and visual support conditions. Because of the stopping distance algorithm, these results were strongly related to the velocity around the blind spot position. Figures 7 and 8 show the vehicle behavior for elderly and younger drivers, respectively. The blue dashed curves represent mean velocity and acceleration; the blue shaded areas represent the corresponding standard deviations. The black-dashed line at 982 [m] indicates the blind spot position beyond which the driver's visual support field was fully restored. The red curve denotes the speed profile (mean) of four driving instructors (over 14 runs), obtained from another experiment around the same intersection [47]. The reduction in the standard deviation of the velocity data confirms that the vehicles were successfully guided to the reference terminal velocity.

3.2. Acceptance

The usefulness and satisfaction scores on the driver acceptance questionnaire are shown in Figure 9: The blue and red objects indicate the rating scores for visual support and full support conditions, respectively. In terms of usefulness and satisfaction, most participants in both age groups gave the support scenarios of visual support and full support conditions a favorable score. A part of the results for the survey regarding the impressions of the system is presented in Figure 9: Here, the blue and red objects indicate the rating scores for the elderly and younger participants, respectively. The proposed approaches were evaluated positively on the question "To what extent did you feel your driving was interrupted by the activation of ADAS?" The result of the Mann-Whitney U test indicated statistically significant between visual support and full support conditions for the elderly participants ($p < 0.05$). Thus, the elderly participants under visual support condition rated as positive than that under full support condition. Moreover, most of the younger and elderly participants answered that they were self-motivated in performing the safety confirmations: only three elderly participants under visual support condition answered on the negative side (individual scores < 3.5).

4. Discussion

In this study, we investigated the effects of proactive braking intervention and visual support cues on elderly and younger drivers' driving performance, and in particular on the drivers' ability to respond to information in potentially hazardous situations. The driving experiment involved two age groups (younger and elderly) and three driving conditions. The main differences between the elderly and younger adults pertained to their driving experience and TMT scores. The baseline was standard condition, and two intervention groups, pertaining to visual support and full support conditions, were established. Under visual support condition, visual support cues with the "slow down symbol" were provided to arouse attention. By contrast, under full support condition, the ADAS provided automatic deceleration control for safety. In the public road driving experiment, the test section and test scenario were established, and driver behaviors were evaluated.

Our hypothesis was that the participant was made more aware of the potential hazards through the activation of the proposed approaches; the hypothesis would be confirmed if drivers using the approaches demonstrated more reactive behaviors that enhanced safety (in particular, if they carefully searched for blind spots). Statistical analysis of the results revealed substantial differences in driver behaviors across age groups and driving conditions. Significant effects from attention-arousing cues on reducing vehicle velocity and directing the driver's face to blind areas were not observed, and the terminal velocity when passing blind intersections after receiving such cues reflected the driver's risk tolerance, possibly different from that of an expert. On the other hand, automatic safety control was observed to have significant effects on the variables of interest, and, under a safety-first policy, the ADAS forced the vehicle to reach a terminal velocity that would mitigate or eliminate the damage from the covert hazard.

In this study, individual differences in the tolerance of perceived risk across age groups and driving conditions were investigated. From the results of the correlation analyses between dependent variables, we found that, with attention-arousing cues, the impact of individual differences on reducing the vehicle velocity and directing the driver's face to the blind areas was greater for the younger participants than for the elderly ones, whereas the reverse was true with automatic safety control. Although the ADAS executed the preventive measure under a safety-first policy, more than half of the elderly participants applied the brakes themselves. Thus, they were able to perform additional safety confirmations; as the velocity when passing the blind spot position was further decreased by the drivers' actions, the maximum face yaw angle tended to increase. This suggests that the elderly participants were made more aware of the potential hazards by the automatic safety control.

The differences between younger and elderly participants' interactions with the proposed ADAS may be caused by differences in driving experience. In previous research, inexperienced drivers have been found to have poor hazard-perception performance [28, 52]. In the present experiment, the driver approached a blind intersection where building walls limited the field of view. The blind intersection functioned as a foreshadowing element (or precursor) [52], and the driver was faced with the covert hazard that an obscured cyclist or pedestrian might emerge. The relationship between the foreshadowing element and covert hazard was indirect, in contrast to a scenario with an overt hazard and visible emergence. The driving-simulator experiment by Crundall et al. [52] revealed that inexperienced drivers were likely to miss hazards that were obscured by the environment, such as a pedestrian emerging from behind a parked vehicle. The present study suggests that drivers of varying experience respond differently to potentially hazardous situations when supported by automatic safety control. The major finding was that both younger and elderly participants were more likely to direct their faces to the blind areas when supported by the automatic safety control than when given attention-arousing cues: the involuntary vehicle slowdown enables the driver to perform safety confirmation pertaining to the blind spots. These results essentially support our hypothesis.

The drivers' behavior analysis was focused when the ADAS initiated or finished the deceleration control owing to the proactive braking intervention approach. We found that it was not easy for drivers to harmonize their behavior with the machine's intent. Although awareness of the blind intersection's location was enhanced by the system providing auditory and visual support cues, the actions of releasing the accelerator before the initiation of braking intervention and initiating the accelerator after the end of the braking intervention were not always successful. By contrast, the ADAS attempted to alleviate conflicts between human and machine intent, because the driver's accelerator input was disabled during the intervention. Thus, we could confirm that the function of disabling the accelerator was useful for guiding foresighted driving behavior based on a machine-initiated strategy, while the highly selective manner in which the human's and the system's braking actions were coupled was also effective for reflecting the human's intention.

The maximum value of the collision velocity was evaluated to determine the effect of the proactive braking intervention on vehicle safety. Based on the behavior of expert drivers, the reference terminal velocity was set to 8.36 km/h. The value was implicated as the velocity at which a collision with a pedestrian or cyclist is avoidable with the support by an autonomous emergency braking system in critical conditions where obstacles suddenly appear in front. The observed longitudinal motion of the vehicle indicated that the guidance to this reference velocity was adequate. The acceptability of the proposed approaches was also evaluated. The finding was that the drivers rated the support scenarios positively in terms of the usefulness and satisfaction when they were guided to the instructor's longitudinal vehicle motion. In this study, the data of some participants who did not intend to decelerate were excluded from the analysis. Therefore, the acceptance of ADAS when driver intent did not match the supported scenarios should be investigated through further data collection. In our future work, options for improving acceptability are: 1) improvement of the calculation algorithms to determine the reference terminal velocity depending on driving context [53], and 2) further extension of the scenarios for the use of the proactive braking intervention. Currently, incident data are registered in the near-crash database of the Tokyo University of Agriculture and Technology. Through machine learning studies using this database [54, 55], a potential risk-level estimation scheme is expected to be introduced into the process of calculating the reference terminal velocity.

There are other limitations on the findings of this study. Although the effects of the driver support on the elderly and younger drivers' performances were investigated, the relationship between driving performance and abilities related to the attentional function was not considered. In addition, the participants were not screened by near vision tests at the distance at which the display was presented to them. The near vision affects their ability to see and interpret the HUD contents on the display. The individual differences in the visual support and auditory functions of elderly drivers should be taken into account in the assessment. Thus, the diversity of elderly drivers must be further discussed, and more data should be obtained for elderly drivers in scenarios supported by the proactive braking intervention to understand their interactions with the new ADAS. The experiment pertains to a within-subject design. Driver behaviors were evaluated in only one test scenario (occlusion); they should be investigated in the context of other overt and covert hazards, and mixtures of the two. Driver behaviors are also affected by such factors as traffic flow, lighting, time of day, and weather; future experiments should be conducted in multiple locations with different environmental contexts. In this work, we only considered situations in which the pedestrian or cyclist did not cross the road. It would be necessary to evaluate the performance of the driver override in the context of the early intervention. The investigation of the possible negative effects of the intervention is inadequate. Finally, although we analyzed short-term effects on the driver behavior, long-term behavioral adaptations must also be studied. In future work, we plan to address the aforementioned issues through public-road driving experiments.

5. Conclusions

This study was designed to examine the effects of proactive braking intervention and visual support cues on the driving performance of elderly and younger individuals. A public-road experiment was conducted with 108 participants. Significant differences were found between the two age groups; for example, elderly drivers seemed less inclined to rely on the automatic system and would apply the brakes themselves after the system had begun doing so. One research question involved how an ADAS might communicate its inherent uncertainty to drivers when exploring an unknown space. The proactive braking intervention attempts to provide a sense of this; furthermore, the system provides drivers with the opportunity to voluntarily perform the action required in unexpected time-critical situations. For example, it was observed that the vehicle slowdown realized through the proactive braking intervention enabled the drivers to perform safety confirmation in blind spots. The participants were more sensitive and/or careful to potential hazards when using/experiencing the proactive braking intervention. This approach could be effective not only for elderly drivers, but also for young or inexperienced drivers. The investigation of possible negative effects will be considered in future work. We encourage the further exploration of driving intelligence to realize hazard-anticipatory driving.

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