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TRIAL VERIFICATION OF HUMAN RELIANCE ON AUTONOMOUS VEHICLES FROM THE VIEWPOINT OF HUMAN FACTORS

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Abstract. *Recently, there has been an increasing interest from automakers and other parties in developing autonomous vehicles. This study investigates the reliance of drivers on autonomous driving with regard to human factors as there have been limited studies that have investigated this aspect. With regard to eye movement, nearly all of the drivers tended to look toward the central area when driving a manual vehicle. Conversely, they tended to look to the left and right of the center during autonomous driving scenarios. With regard to the brake (preparation) behavior, the percentage concordance of nearly all of the drivers was from 13.3% to 49.2%. However, a driver focusing on the central area during autonomous driving had a percentage concordance of the brake preparation behavior of 98.8%, which is extremely high. These results indicate that there is a tendency for nearly all drivers to rely on autonomous driving systems; however, some drivers did not rely on them. When verifying the drivers' levels of sleepiness, it was found that all drivers tended to become sleepier over time during autonomous driving. Therefore, based on human factors, it appears that drivers tend to rely on autonomous driving systems.*
Keywords: Autonomous driving, Human factors, Dependence, Eye gazing, Brake behavior, Sleepiness level

1. **Introduction.** Recently, there has been an increasing interest from automakers and other parties in developing autonomous vehicles. At the New York World's Fair in 1939, General Motors hosted an exhibit called Futurama, where they envisioned a future in which a large number of autonomous vehicles drove through cities filled with green areas. Therefore, the idea of autonomous vehicles is not a recent one. Several attempts have been made to develop autonomous vehicles, such as the Stanford Cart [1,2], Boss by Carnegie Mellon University [3], Shelly by Stanford University [4], and the Toyota Prius by Google [5]. Moreover, an increasing number of automakers and other parties have unveiled their plans for the future. In December 2013, Ford unveiled a self-driving research car called the modified Fusion Hybrid, which was developed with the University of Michigan and State Farm insurers [6]. Additionally, Ford announced that it will mass produce a fully autonomous self-driving car without a steering wheel by 2021 [7]. In 2017, Volvo announced that it will introduce 100 autonomous vehicles at Gothenburg, Sweden [8]. Nissan and Renault, its business partner, have claimed that they will offer more than 10 cars with a range of autonomous features by 2020, which will particularly be "mainstream, mass-market cars at affordable prices" [9].

With these developments, the idea of a fully autonomous vehicle rather than just a partially autonomous vehicle [such as a vehicle equipped with an adaptive cruise control (ACC) or a lane-keeping assist system] may come true. An IHS automotive study predicted that there will nearly be 54 million self-driving cars worldwide by 2035 [10]. This study also predicted that after 2050, nearly all vehicles in use will likely be self-driving cars or self-driving commercial vehicles [10]. It is expected that as more autonomous vehicles are developed, the relationship between vehicles and drivers will become increasingly complex. The autonomous technology can be considered as a technology employing a five-part continuum, as suggested by the US National Highway Traffic Safety Administration, with different benefits being realized at different levels of automation [11,12].

Because the technology underpinning autonomous vehicles is highly feasible, the mass production of autonomous vehicles is anticipated; however, several problems need to be resolved before mass producing these vehicles. These problems include revisions to existing laws and the development of necessary infrastructure such as person-to-person, vehicle-to-person, vehicle-to-infrastructure, and vehicle-to-vehicle communication. Additionally, because the current focus of developers is on realizing level 3 autonomous vehicles, human factors should be considered with respect to the driving of autonomous vehicles. One study has reported that drivers are incentivized and their mental workload (such as the effort of extending an arm) is reduced when ACC is used [13]. This study also suggested that drivers tend to rely heavily on the ACC system and that they can rely too heavily on it. Therefore, it is essential to determine whether a driver considerably relies on an autonomous vehicle. The manner in which a driver handles a normal situation or relies considerably on an autonomous vehicle is also important. If the results reveal that the drivers have a tendency to excessively rely on the autonomous features, then this tendency could be considered as a negative effect of such vehicles. Furthermore, mechanisms would need to be developed to deal with such scenarios.

Previous research has shown that the behavioral measure of trust in an autonomous vehicle can be measured based on the movements of a driver's body party (e.g., their heads, hands, and feet) as they experience a simulated autonomous system [14]. However, in this study, the trust in the autonomous vehicle was solely determined based on the body movements. Other human factors were not considered. Unfortunately, only few studies have investigated drivers' reliance on autonomous driving systems in vehicles with regard to the human factors.

Autonomous driving has been found to be a considerably effective and useful system for various drivers because operations to control vehicles, such as the acceleration and steering controls, are operated automatically. Consequently, the mental workload of drivers is reduced during autonomous driving and drivers may tend to rely on autonomous driving systems. However, if they considerably rely on these systems, they may not be able to prepare themselves for system failures. In such a scenario, drivers may be unable to control a vehicle well because they are not accustomed to autonomous driving and their recognition and judgment cannot adapt to manual driving conditions. As such, the determination of whether drivers tend to depend on autonomous systems and how they tend to depend on such systems serves as important information for drivers to conceive and effectively manage an autonomous driving system. Especially, the appeal effect increases about this important information if we can show the driver's state on autonomous driving from biological indicators.

This study investigates drivers' reliance on autonomous vehicle systems from the viewpoint of human factors. This remainder of this study is organized as follows. The experimental situation and methods are described in Section 2. Section 3 discusses the results of the experiment. Section 4 presents an analysis of the results. Finally, Section 5 presents the conclusions.

2. **Experimental Situation in a Driving Simulator and Determining the Reliance of Drivers on Autonomous Driving.** Five male subjects aged 22-23 years old participated in the experiment. A driving simulator (D3sim, Mitsubishi precision Co., Ltd.) was used to investigate the effect of human factors on autonomous driving. The drivers were instructed to drive in an urban area course for approximately 15 min while controlling the steering wheel, accelerator pedal, and brake pedal on their own. This condition was referred to as the manual driving scenario. After a break of approximately 15 min, the drivers were instructed to drive on the same course for another period of approximately 15 min; however, in this session, the steering wheel, accelerator pedal, and brake pedal were automatically controlled. Therefore, the drivers did not have to control the vehicle themselves. This condition was referred to as the autonomous driving scenario.

The driving time of approximately 15 min was chosen following a report [15], which stated that the percentage of people that required a driving time of 5-10 min in one direction by car for shopping was 36.2%, whereas the percentage of people that required a driving time of 10-15 min was 26.8%. Therefore, more than half of the drivers required a driving time of 5-15 min in one direction when going shopping by car. Incidentally, the number of people that drove for over 15 min exhibited the same trend on a homeward. Hence, the driving time was chosen to be approximately 15 min.

Drivers were also asked to press the brake pedal either when the presence of a collision risk was determined, a system failure suddenly occurred, or the drivers were unable to control the driving simulator. It should be noted that in reality, no system failure occurred. However, in the autonomous driving scenario, an event wherein a person suddenly rushes out onto the course after approximately 6 min of driving was included.

Our previous studies [16,17] showed that the information-processing resources of the drivers do not focus on the leading vehicle but on the subjects around the leading vehicle, such as the side strip for pedestrians, roadside trees, and road signs, when they are in an unfocused driving state. From these studies, it can be inferred believing that drivers become unfocused if they considerably rely on autonomous driving systems. Consequently, the dependency of drivers on autonomous driving can be estimated from their eye movements. Additionally, from the standpoint of the "delegation of authority" [18], drivers' brake behavior can be a factor for judging their reliance on an autonomous system. Furthermore, previous research has reported that monotonous work makes people sleepy [19]. Autonomous driving can be thought of as a type of monotonous work-like activity, making drivers sleepy. In other words, the reliance of drivers on autonomous driving systems can be determined based on their sleepiness level. As a result, eye movements, brake (preparing) behaviors, and subjects' sleepiness levels were adopted as biological indicators that could be used to assess the differences in the human factors for autonomous and manual driving.

In both the manual and autonomous driving scenarios, drivers' eye movements, facial expressions, and brake behaviors as well as the experimental situation were recorded and measured. Drivers' eye movements were recorded and measured using an eye-mark recorder (T.K.K.2950 TalkEye Lite, Takei Scientific Instrument Co., Ltd.), while drivers' facial expressions and brake behaviors were recorded as motion pictures using a CMOS camera (YT-704, YK Musen Co., Ltd.) and a small infrared camera (YM-203C, YK Musen Co., Ltd.), respectively. The experimental situation was recorded using a video camera (Everio, JVC). These scenes were combined into a single screen using a split-screen unit (AQ-400, Carrot Systems, Inc.) and recorded using a DV deck (GV-HD700, Sony Corporation). A scene recorded using the DV deck is shown in Figure 1. In addition, the subjects were informed of the purpose and content of the experiment and they provided informed consent in writing.

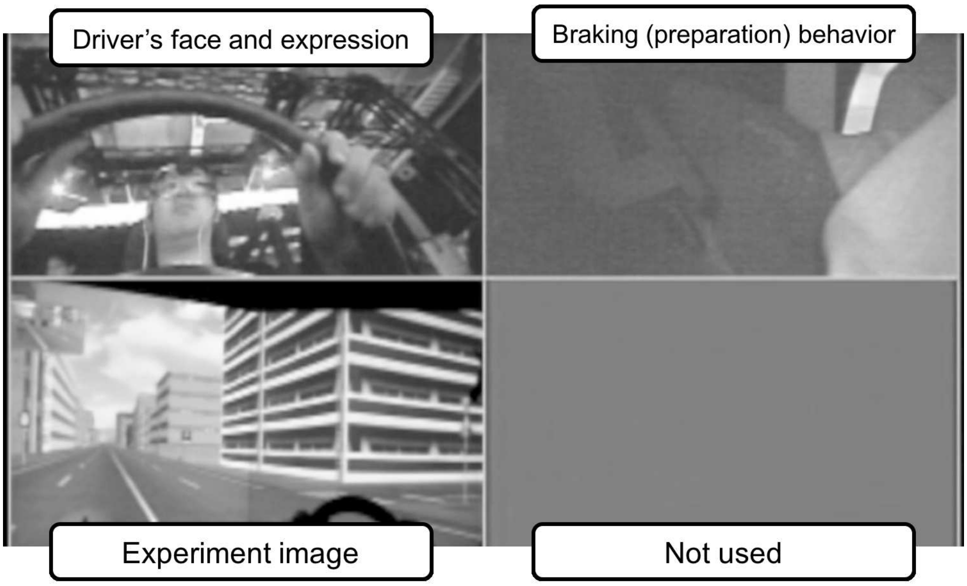

Figure 1. Experimental situation. Upper left panel: a driver's face and his expression. Upper right panel: brake (preparation) behavior. Lower left panel: experimental image. The lower right panel was not used to capture images.

All experimental procedures were approved by the Research Ethics Committee of the Aichi University of Technology (#28-5).

3. **Results.** The time-series data of the eye fixation probability of horizontal component, brake (preparation) behavior, and sleepiness levels are shown in Figure 2. In this figure, only one driver's data are shown, serving as an example of the obtained results.

In Figure 2(a), the x-axis indicates the position of the line of sight (zero indicates the center, and positive values indicate the direction to driver's right), while the y-axis indicates the time in seconds. The time-series data are shown as a heat map per 10 s. In this heat map, the white area indicates that the probability of the driver looking at an area for 10 s is close to 1. In other words, the white area indicates that the driver gazes in that direction at that time. Conversely, the black area indicates that the probability of the driver looking at an area for 10 s is close to 0. Incidentally, the sampling time of the eye-mark recorder is 30 fps; therefore, the 10 s data comprise 300 frames.

Figure 2(a) shows that the gazing time and gazing tendency near the center of the field view (i.e., 0°) are long and high, respectively, before approximately 200 s in the manual driving scenario. However, the left and right areas with respect to the center became brighter. As a result, the gazing time and gazing tendency to the left and right areas became long and high, respectively. Conversely, the gazing time and gazing tendency to the left and right areas with respect to the center were found to be long and high, respectively, at all driving times in the autonomous driving scenario. Additionally, the gazing time and gazing tendency to the left and right areas with respect to the center became longer and higher, respectively, than those in the manual driving scenario.

The time at which brake preparation occurs for the manual and autonomous driving scenarios is shown in Figure 2(b). An evaluator watches the moving picture of the brake behavior captured by the infrared camera and visually evaluates whether the driver placed his foot on the brake pedal or pressed it. In Figure 2(b), the solid line indicates the brake

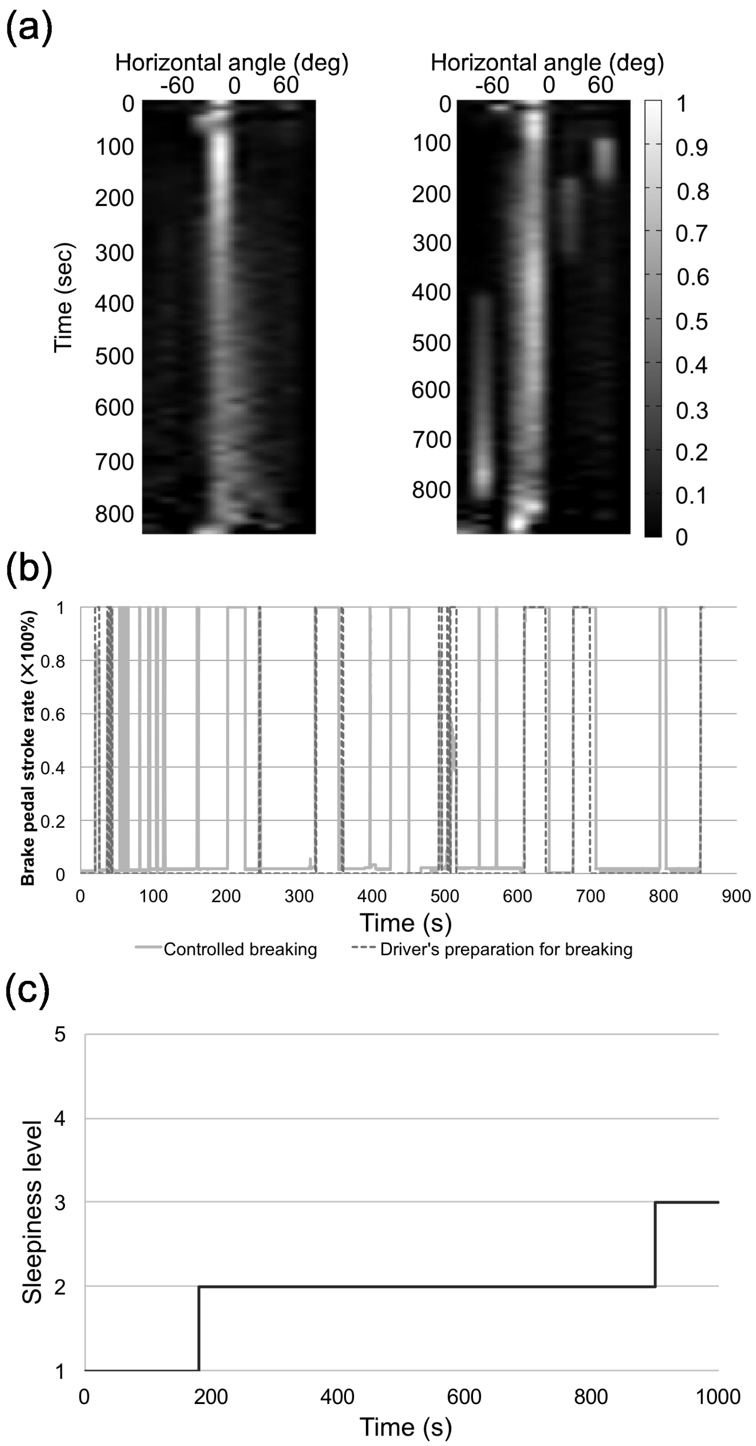

FIGURE 2. Data measured for a specific driver: (a) eye fixation probability in the manual driving (left-hand side) and autonomous driving scenarios (right-hand side), (b) brake (preparation) behavior, and (c) time series of the sleepiness level

behavior of the autonomous brake and the dotted line indicates the brake (preparation) behavior of the driver.

The time-series data of the driver's sleepiness level from the start to the end of the driving exercise are shown in Figure 2(c). These data are based on the moving picture captured by the CMOS camera. NEDO's evaluation method, which is a subjective estimation method used by the evaluators examining the moving pictures, was used to evaluate the drivers' sleepiness levels [20].

According to this evaluation method, the drivers' sleepiness levels were categorized into five levels based on the drivers' behaviors. Several evaluators simultaneously observe the moving picture of a driver's face and judge the sleepiness level by means of the majority rule based on Table 1 every 5 s, which corresponds to the sleepiness level based on NEDO's index. Therefore, a driver's sleepiness level can be quantified.

Table 1. Sleepiness levels and driver's behavior based on the NEDO index

Sleepiness level	Driver's behavior
Level 1	Not at all sleepy (the subject's eye movements are quick and frequent)
Level 2	Slightly sleepy (the subject's eye movements are slow, and the mouth is open)
Level 3	Sleepy (the subject's eye blinks are slow and frequent, his mouth moves, and the subject corrects his posture)
Level 4	Pretty sleepy (the subject displays a conscious eye blink, shakes his head, and yawns frequently)
Level 5	Very sleepy (the subject closes his eyes and leans his head back and forth)

4. Considerations of the Reliance of Drivers on Autonomous Driving in Terms of Eye Gazing, Brake (Preparation) Behavior, and Sleepiness Level.

4.1. Comparison of the probability of eye gazing between the manual and autonomous driving scenarios. Figure 3 shows the time-series heat map of each driver's horizontal component of eye fixation rate. Table 2 lists the mean and standard deviation of the probability of eye gazing to the left-hand side from the center of the field view by $-20°$ and to the right-hand side from the center of the field view by $20°$ during the manual and autonomous driving scenarios. The thresholds of the left side of $-20°$ and those of the right side of $20°$ were based on a previous study, which showed that the effective field of view of a human eye is from $4°$ to $20°$ in the horizontal direction [21]. Therefore, the threshold is $\pm 20°$ in the horizontal direction from $0°$, which is the state in which a driver directly looks forward [16,17]. In Table 2, the probability of the drivers' eye fixation at the center when the vehicle is moving forward in the manual driving scenario is lower than that in the autonomous driving scenario for Drivers A, C, and E. Conversely, the probability of their gaze being fixed onto the left or right of the center in the autonomous driving scenario is greater than those in the manual driving scenario. As discussed in Section 1, previous research [16,17] showed that the information-processing resources of a driver in an unfocused driving state do not focus on a leading vehicle but on the subjects around the leading vehicle, such as the side strip, roadside trees, and road signs. Drivers may not focus on the leading vehicle and/or subjects, such as vehicles or pedestrians rushing out into the traffic, and may enter an unfocused driving state due to their dependence on autonomous driving systems during driving. The probability of eye fixation on the left and/or right areas seems to increase in an unfocused driving state that is induced by the dependence on autonomous driving in the cases of Drivers A, C, and E.

In the case of Driver B, the probability of fixation in the direction of the leading vehicle is not significantly different during manual and autonomous driving. When comparing autonomous driving to manual driving, the primary difference is that the probability of

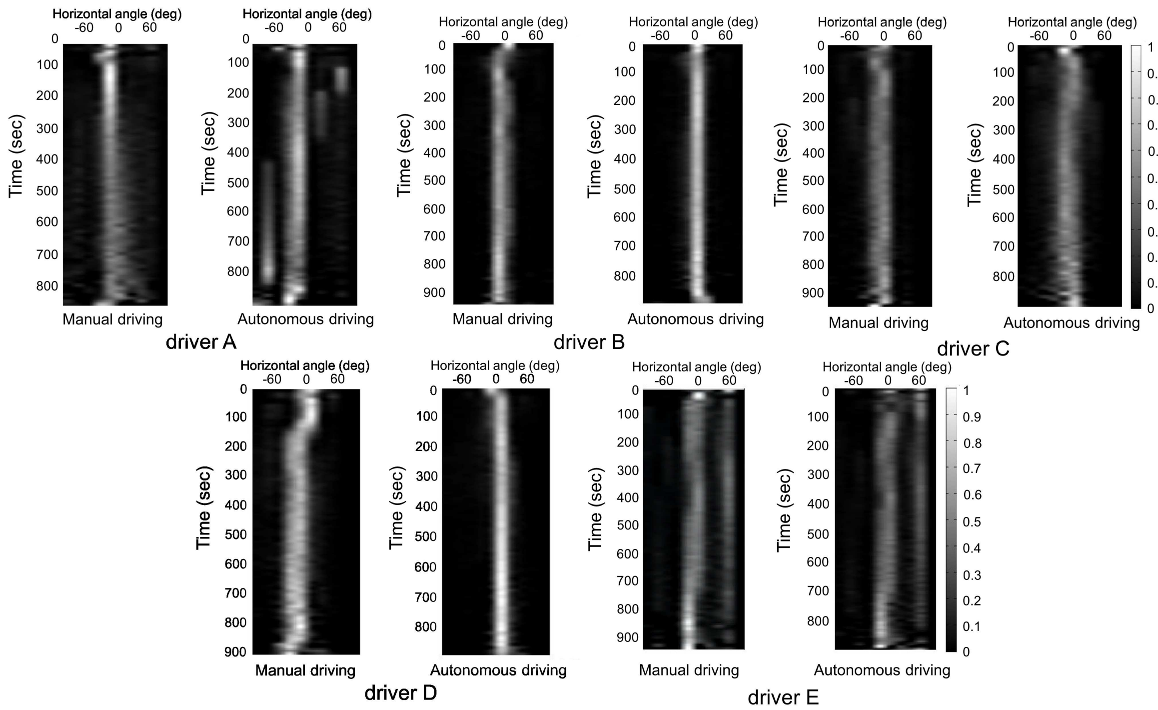

FIGURE 3. Time-series heat map of the drivers' horizontal eye fixation rate

TABLE 2. Horizontal eye fixation rate of the drivers (left side of the center of the field view, center of the field view, and right side of the center of the field view). The values obtained for automated and manual driving are compared. **: $p < 0.01$ (statistically significant result between manual and autonomous driving via t-test).

Target	Left		Center		Right	
	Manual	Automated	Manual	Automated	Manual	Automated
Driver A	0.204±0.064	0.402±0.168	0.580±0.080	0.431±0.100 (**)	0.208±0.064	0.157±0.119 (**)
Driver B	0.901±0.049	0.046±0.025	0.866±0.643	0.856±0.043	0.041±0.032	0.098±0.031 (**)
Driver C	0.133±0.059	0.218±0.055	0.800±0.060	0.685±0.081 (**)	0.067±0.024	0.097±0.051 (**)
Driver D	0.378±0.134	0.048±0.038	0.577±0.122	0.812±0.054 (**)	0.045±0.029	0.141±0.047 (**)
Driver E	0.073±0.031	0.069±0.025	0.576±0.086	0.536±0.096 (**)	0.342±0.087	0.396±0.107 (**)

fixation on the left area is converted to that on the right area. The reason behind why Driver B gazes in the direction of the leading vehicle during autonomous driving appears to be because of his nervousness about the probability of the occurrence of an autonomous system failure (Section 4.2).

As for Driver D, the probability of fixation in the direction of the leading vehicle during autonomous driving is greater than that during manual driving. The questionnaire given to Driver D following the driving exercise indicates that he often thought of something else besides driving during autonomous driving. Therefore, this caused an increase in the probability of his fixation in the direction of the leading vehicle.

4.2. **Comparison of the probability of eye gazing between manual driving and autonomous driving.** The brake behavior seems to reflect the drivers' reliance on the preventive safety technology. A previous study showed that the brake response time (RT) and time to collision reflect the drivers' reliance on preventive safety systems, such as ACC [22]. Similarly, the difference in the time in which the drivers operate the brake during autonomous and manual driving appears to reflect their reliance on an autonomous system, particularly the preventive safety systems of the autonomous vehicle. Therefore, in this study, the concordance rate of the timing of the drivers' brakes and the autonomous brake was used as a factor to determine the drivers' reliance on autonomous vehicles.

4.3. **Brake (preparation) behavior.** Table 3 lists the concordance rates of the timing of the drivers' brakes and the autonomous brakes during autonomous driving. The drivers' brake behavior was decided by visually determining whether they are placing their foot on the brake pedals or pressing them as per the moving pictures of their feet, as mentioned in Section 2. In Table 3, the percentage concordance of Drivers A, C, D, and E ranges from 13.3% to 49.2% and the percentage concordance, which means that a driver places his foot on the brake pedal or presses it during autonomous driving, is at most half of the timing of the autonomous brake. This indicates that the drivers rely on autonomous driving and autonomous brake systems. However, the percentage concordance for Driver B was 98.8%. He actually placed his foot on the brake pedal for most of the driving period. The results of the questionnaire given to Driver B following the exercise show that the driver was instructed about the occurrence of a system failure in the autonomous driving system, making the system unreliable. Therefore, he thought that he had to grasp the steering wheel and apply the brake pedal manually. Consequently, Driver B did not rely on the autonomous driving system and his brake behavior supports his decision.

Table 3. Concordance rate of the brake (preparation) behavior and the automated brake

Driver	Concordance rate (%)
Driver A	42.2
Driver B	98.8
Driver C	49.2
Driver D	27.9
Driver E	13.3

Only Driver B applied the brake pedal at the moment a pedestrian rushed out into the traffic. However, some drivers placed their feet on the brake pedal and only pressed the brake pedal after the pedestrian had rushed in front of the vehicle. Therefore, except Driver B, they may have thought or assumed that the vehicle would not collide with the pedestrian because of the autonomous braking system.

From the above results, it is necessary to verify human reliance on autonomous driving systems based on the drivers' steering behavior because steering is controlled automatically. In contrast, in the experiments, all drivers lightly placed their hands on the steering wheel, making it impossible to verify their reliance on autonomous driving systems from their steering behaviors.

4.4. **Increasing sleepiness levels during autonomous driving.** The time-series change in the sleepiness levels of Drivers A-E was estimated based on the NEDO index, and the results are shown in Figure 4. A remarkable increase in the sleepiness level is shown for Driver A; his sleepiness level transitions from level 1 at the start of the experiment to level

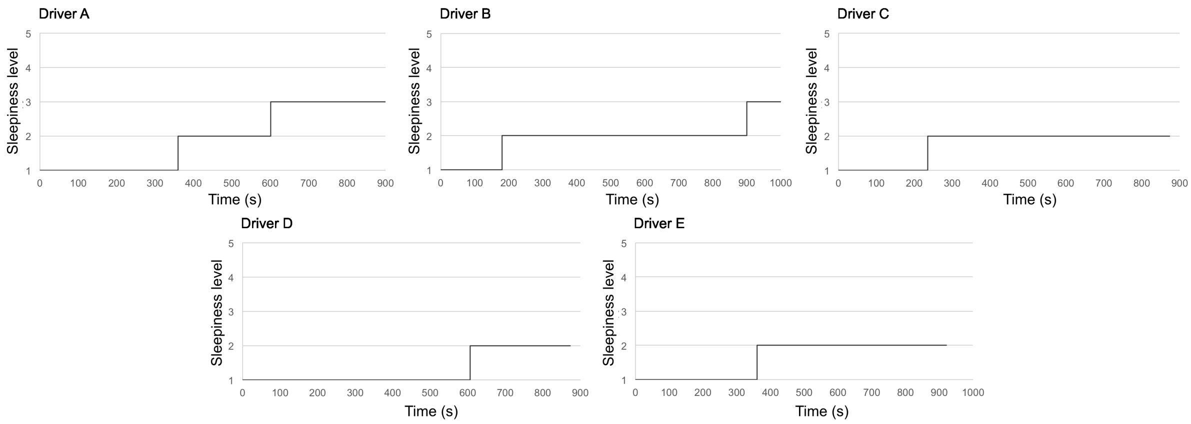

FIGURE 4. Time-series data of the drivers' sleepiness levels during autonomous driving according to the NEDO index

3 by the end of the experiment. He actually stretched himself and yawned after driving and looked considerably sleepy. The sleepiness levels of Drivers C, D, and E transition from level 1 at the start to level 2 at most. Therefore, it is suggested that the sleepiness level of these drivers tended to be lower even if they drove for approximately 15 min.

Conversely, the sleepiness level of Driver B increased to level 3 immediately after finishing the autonomous driving exercise; however, this result does not match the results of the questionnaire reported in Section 4.2 because Driver B did not trust the autonomous driving system and was anxious. The questionnaire given to Driver B shows that he felt bored by the end of the driving exercise despite being nervous, and this caused a slight increase in his sleepiness level.

5. **Conclusions.** Herein, the probability of the drivers' reliance on autonomous driving systems was verified using eye movements, brake (preparation) behaviors, and sleepiness levels, which were determined using the NEDO index. As a result, particular eye movements, brake behaviors, and increasing sleepiness levels were demonstrated by Drivers A, C, D, and E due to their reliance on autonomous driving systems. Conversely, Driver B tended to gaze in the direction of the leading vehicle and applied the brake pedal at the same time as done in the autonomous driving scenario. This is because the driver did not rely on the autonomous driving system as he had received prior explanation of the scenario.

It is true that drivers tended to rely on autonomous driving systems due to the convenience of using them. However, it is possible that errors, such as sensor malfunctions, could occur in autonomous vehicles; thus, some of their functions may not work. In such a scenario, drivers may fail to appropriately deal with the system failure. Even for level 3 autonomous driving, drivers are likely to rely on autonomous driving systems according to the tendencies of eye fixation, brake (preparation) behaviors, and increasing sleepiness levels. Therefore, it is uncertain whether drivers can appropriately deal with any system failures that may occur. Conversely, it is possible that appropriate information about the probability of the failure of a system could inhibit the drivers' reliance on an autonomous driving system, as indicated by the results obtained from Driver B. In addition, such a driver could use an autonomous vehicle system while preparing for a sudden event, such as a system failure, to reduce his mental workload.

Herein, eye movements, brake (preparation) behaviors, and sleepiness levels were used to verify human reliance on autonomous vehicles. In the future, other physiological and psychological measurement methods will be used to verify whether drivers rely on autonomous vehicles. In addition, all drivers in our experiments were male university students. Therefore, female and older drivers should also be considered in future experiments to further examine human reliance on autonomous vehicles.

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