# Bringing a Vehicle to a Controlled Stop: Effectiveness of a Dual Control Scheme for Identifying Driver Drowsiness and Preventing Lane Departures under Partial Driving Automation Requiring Hands-on-Wheel

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*Abstract*—**Partial driving automation systems execute sustained lateral and longitudinal control, while humans are required to supervise the automated driving features. Similar with drivers using manual driving settings, those using automated driving systems may also experience drowsiness. However, existing systems that aim to detect driver drowsiness tend to be unreliable. This study applies a dual-control scheme in the partial driving automation context in which the driver must keep their hands on the vehicle's steering wheel. This scheme executes a partial steering control when a vehicle lane departure is anticipated (because of inappropriate torque input) and then activates a deceleration control if the driver does not properly perform the required action. To determine whether the driver is supervising the partial driving automation, the scheme attempts to create an opportunity for driver-automation interactions. Thus, the controller's objectives are twofold: safety control and driver state identification. This study investigated the effectiveness of the scheme for identifying driver drowsiness and preventing lane departures using only vehicle information. Twenty drivers participated in a fixed-base driving simulator experiment in a sleep-inducing environment. While we observed cases in which the system could effectively bring the vehicle to a controlled stop, the timeliness and accuracy of the driver state identification remained as issues owing to indirect links between the drivers' drowsiness level and controller activation. We conclude that although the dual-control scheme is a useful mechanism to avoid lane departures, the driver state identification needs to be improved to ensure timely and effective detection of driver drowsiness.**

*Index Terms*—**Driving safety, partial driving automation, human-machine interaction, driver monitoring, dual control.**

## I. INTRODUCTION

Similar to drivers using manual driving settings, those using driving automation systems may also suffer from sleepiness and fatigue [1]–[3]. Daytime sleepiness can be attributed to the time of day (circadian rhythms), extended duration of wakefulness, and sleep deprivation [4], [5]. Fatigue can be classified into types, active fatigue and passive one [4], which are produced by the characteristics of driving, such as task demands. Active fatigue is produced by increased task load situations (e.g., high-density traffic and poor visibility), whereas passive fatigue is produced by task underload (e.g., monotonous and predictable drives [6], [7], and supervision of automated driving systems [1]). The effects of sleepiness and fatigue on driving performance decrements have been widely discussed in experimental studies [8]–[10], and sleepiness and fatigue symptoms have been found to contribute to the deterioration of driving performance [10].

The Society of Automotive Engineers (SAE) defined five levels of driving automation (LoDA) [11] from the perspective of function allocation between the driver and the automation. It defined LoDA 2 (i.e., partial driving automation) as a system in which automation executes sustained lateral and longitudinal vehicle motion control, but not complete object/event detection and response (OEDR). In partial driving automation, humans engage in a combination of automated driving features, and are required to supervise the automated driving features and complete OEDR subtasks. Thus, humans must fulfill the role of the driver and be responsible at all times to complete strategic, tactical, and operational tasks [11], [12].

Partial driving automation systems can be divided into two types: hands-on automated driving systems that require drivers to hold the vehicle's steering wheel (e.g. Autopilot [13]) and hands-off automated driving systems that do not (e.g., Super Cruise [14] and ProPilot 2.0 [15]). In general, a hands-off automated driving system is capable of accurate vehicle localization using a digital map [15]. By contrast, a hands-on automated driving system without a digital map is less capable of localizing the vehicle's position. Therefore, hands-on automated driving systems expect that OEDR subtasks can be completed through the driver's active involvement via shared control [16]. However, even in hands-on automated driving systems, the drivers are passive operators. While the system actively performs lateral control, drivers are required to maintain a light grip on the wheel so as not to input unnecessary steering torque. Although drivers remain in command of

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their driving, it would be unrealistic to expect that drivers are always ready to respond as needed [17]–[19]. Thus, sleepiness and passive fatigue, which deteriorate driving performance [4], [5], are highlighted as issues of human factors in the context of hands-on partial driving automation.

Driver monitoring for detecting sleepiness and fatigue can be categorized into two methodologies [20]: direct driver-related and indirect driving-related measurements. The former approach can be classified into physiological measurements, such as Electroencephalogram (EEG) [21], [22] and Electrocardiogram (ECG) [23]; behavioral measurements, such as frequent driver body movements [24] measured by pressure distribution sensors, nodding or swinging heads [25]–[27], slow eyelid closure [28], eye blink frequency and eye closure duration [29], and percentage of eyelid closure (PERCLOS) [30], [31] as determined by camera sensors; and facial expression recognition [32]–[34]. Non-intrusive systems are suitable to detect drowsiness of drivers during automated driving [35]. The latter approach involves vehicle-based measurements, such as movements of the steering wheel and vehicle lateral motion [29], [36]–[38]. For example, as the drowsiness level of the driver increases, the standard deviation of the lateral position (SDLP) increases [29]. However, existing methods tend to be unreliable, particularly because of individual variations in physiological and behavioral properties. Classification methods, such as artificial neural networks [23], and support vector machines [39], have not adequately addressed the individual variation problem. Ingre et al. [29] found that individual drivers have different SDLPs, even at similar drowsiness levels. It is not easy to adjust a threshold that is applicable to all drivers for classifying drivers' drowsiness levels. Facial expression recognition does not properly work if a mask or sunglasses cover the driver's face. Hence, a reliable approach based on both direct driver-related and indirect driving-related measures is one of the trends in technological development [40].

Vehicle lateral control, which comprises most partial driving automation systems, includes the following functions: lane centering systems (LCSs) and lane departure prevention (LDP). These lateral controls provide haptic feedback to the drivers, and haptic driver–system interactions can be created at the operational level [41]. However, current partial diving automation systems, which implement sustained lateral and longitudinal vehicle motion control, do not account for the driving context or the behavioral characteristics of drowsy drivers. Thus, when an inappropriate steering action is detected, the system performs LDP to return the vehicle to the center of the driving lane. Although drivers can perceive and recognize the machine's intention via force feedback, the condition with which a driver who is drowsy still tries to continue driving still warrants further examination. Vehicles equipped with partial driving automation systems may have an additional function designed to bring the vehicle to a controlled stop if the driver fails to supervise the feature's performance. Tesla's Autosteer [13] has a mechanism used to detect situations in which the driver takes their hands off the wheel; if Autosteer does not detect the driver's hands on the wheel for a period of time, a flashing light is presented to the driver with an auditory alert, and the following message is displayed: "Apply slight turning force to steering yoke." If the driver repeatedly ignores prompts to take the wheel, Autosteer slows the vehicle to a complete stop. This technological development motivated us to design a haptic driver–system interaction method to identify the driver drowsiness and bring the vehicle to a controlled stop under the context of hands-on partial driving automation.

### A. Strategy to bring the vehicle to a controlled stop

In previous studies, the SAVE (System for effective Assessment of the driver state and Vehicle control in Emergency situations) project [42], which aimed at reducing crashes due to driver states (e.g., states of low arousal and degradation of mental and physical functions), has developed a system that detects impaired driver states and undertakes emergency handling in real time. The system functions to take over control if the driver does not perform properly and fails to respond to *warnings* [43]. In a similar design concept, we proposed *a haptic driver–system interaction method* with a dual-control scheme that attempts to execute vehicle control and driver state identification in the context of manual driving [44]. In the domain of control theory, dual control deals with the control of uncertain systems whose characteristics are unknown [45] and considers the dual role of control signals for control and real-time estimation. The control signals of adaptive systems have the following features: (i) the controlled variable cautiously tracks the target value and (ii) the signals excite the controlled object to enhance the process of parameter identification, so that the control performance improves in future intervals [46]. The controller has two objectives: *action* —to perform safety control based on current information— and *investigation* —to experiment with the system to know and/or learn its behavior. In our previous study, this dual-control scheme was applied to human–machine systems. Thus, the controlled object is a vehicle and the object to be identified via the signal is the driver's state. The present study applies the proposed dual-control scheme to a partial driving automation that requires the driver's hands on the wheel.

We now briefly describe the proposed scheme, which is based on our previous study [44], [47]. The hands-on partial driving automation does not change lanes or overtake other vehicles autonomously without driver input (i.e., turn signal, and then steering), and the drivers are responsible for the steering input even when an LCS is active. Thus, they can override the lateral control by inputting the steering torque. Suppose that a vehicle deviates from a straight driving lane. When the system anticipates that lane departure will occur in 1 s, it implements partial control as the first stage of safety control to prevent lane departure from occurring, as shown in Fig. 1. This first-stage safety control is sufficiently powerful in keeping the vehicle in the driving lane, but it does not bring the vehicle back to the center of the lane, resulting in the vehicle being 0.5 m inside the lane markers, parallel to them. Normally, if the driver supervises the partial driving automation system appropriately, they will implement the steering action to return the vehicle to the center of the driving lane in the event of approaching the lane boundary, as shown in Fig. 2. If the driver implements the proper action within 10 s after the initiation of the first-stage control, the system determines that “the driver has supervised the partial driving automation.” By contrast, if the driver does not implement the proper action within 10 s, the system determines that “the driver failed to supervise the partial driving automation.” Then, it implements the remaining steering control (second-stage control) to return the vehicle to the center of the driving , as shown in Fig. 3. In addition, the system executes deceleration control to bring the vehicle to a controlled stop.

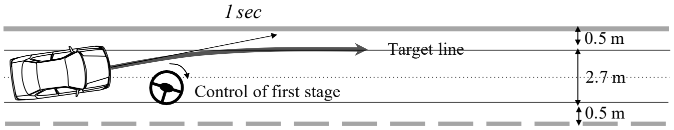

Fig. 1. Control of the first stage to prevent the lane departure.

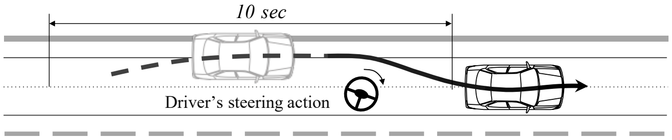

Fig. 2. Driver’s action to return to the center of the lane.

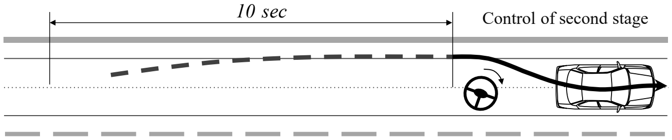

Fig. 3. Control of the second stage to return to the center of the driving lane.

### B. Hypotheses

In previous studies, Naujoks et al. [48] assessed the relationship between the driver’s reactions to the braking lead vehicle and drowsiness level in the context of hands-on partial driving automation, and one predictor for increased reaction time was drowsiness. However, our understanding of the behavioral patterns of a driver who feels sleepy when using hands-on partial driving automation is still limited. Thus, this study aims to evaluate the effectiveness of our dual-control scheme for identifying driver drowsiness and preventing lane departures in the context of hands-on partial driving automation, without relying on direct driver-related measures. In this study, we examined the following hypotheses:

(a) The driver will input inappropriate torque to the steering wheel in conjunction with head pose movements due to driver drowsiness. Moreover, the driver will be unable to maintain a light grasp on the wheel when falling asleep, which may lead to a hands-off-the-wheel situation with improper torque input.

(b) Lane departure occurrence will be predicted due to the conditions under (a). Thus, the proposed approach can prevent lane departures.

(c) If a driver falls asleep, then proper actions to bring the vehicle back to the center of the lane after the activation of first-stage control cannot be implemented. Accordingly, the system deems that “the driver failed to supervise the partial driving automation” and hence activates the deceleration control to bring a controlled stop.

The remainder of this paper is organized as follows: In Section II, we describe an experiment in which data are collected on the driver state and behaviors when the proposed scheme is activated. In Section III, we present the experimental results. Finally, in Section IV, we discuss the effectiveness of the proposed approach.

## II. METHOD

The experiment was conducted with the approval of the ethical review board of the University of Tsukuba.

### A. Apparatus

As shown in Fig. 4, the experiment was performed with a fixed-base driving simulator (Mitsuibishi Precision Co.,Ltd.), which consists of an accelerator, a brake pedal, and a steering wheel (Moog, Inc.). Five computers, connected to the simulation software (D3sim), generated the driving view (approximately 180°). The scenario was presented to the drivers with five monitors (SHARP 42-inch 1920×1080 monitors). The self-aligning torque, which is part of the tire force, was generated by D3sim and was fed back to the steering wheel. In addition, two cameras (Smart Eye) were mounted on the left and right sides of the desk, regarded as the cabin, and they were used to detect eyelid and head pose activities.

### B. Participants

A total of 20 students (Participants 1–20; 14 males and 6 females) aged between 20 and 28 years (mean (M) = 23.1, standard deviation (SD) = 2.05 years) participated in this study. The reward for participation was provided by the university. All the participants possessed a valid driver’s license, and they drove a vehicle at least once a week. They had corrected visual acuity of 0.7 or higher based on the Landolt–ring vision test.

### C. Partial driving automation with the dual–control scheme

A partial driving automation was implemented: a longitudinal control system that automatically maintained the vehicle at a target speed and an LCS that attempted to keep the vehicle’s position in the center of the driving lane. In this experiment, the participants remained in command of their driving, and they could override the lateral control by inputting a torque of at least 0.5 $\mathrm{Nm}$. Thus, the maximum amount of torque assisted by the LCS was set to $\pm 0.5$ $\mathrm{Nm}$ in the context of straight-line driving.

The methods for lane departure prediction, lateral vehicle control, and driver action detection were identical to those

Fig. 4. Fixed-base driving simulator.

TABLE I
DROWSINESS SCALE [33]

| Level | Description |
|---|---|
| 1 | **Not Drowsy**: Eye movement is rapid, and the time between blinks remains stable. |
| 2 | **Slightly Drowsy**: Eye movement is slow. |
| 3 | **Moderately Drowsy**: Blinks are slowly, the mouth moves, or the driver touches his/her face. |
| 4 | **Significantly Drowsy**: Number of blinks increases noticeably, motions unnecessary for driving are observed, yawns are frequent, deep breathing is detected. |
| 5 | **Extremely Drowsy**: Eyelids are almost closed, or the driver's head inclines to the front or rear. |

used in a previous study [44]. When the predicted value of the time margin for lane departure became less than 1 s, the system initiated the first-stage control to prevent the lane departure, where the target line for the lateral vehicle control was changed from the center of the lane to 0.5 m inside the lane markers. The maximum amount of torque assisted by the first-stage control was set to $\pm 3\ \mathrm{Nm}$. When the driver's steering action was not detected within 10 s after the initiation of the first-stage control, the system initiated the second-stage control, where the target line for the lateral vehicle control was changed from 0.5 m inside the lane markers to the center of the lane. The maximum amount of torque assisted by the second-stage control was set to $\pm 3\ \mathrm{Nm}$. At the same time, the system executed deceleration control to bring the vehicle to a controlled stop with a target deceleration of $0.1\ \mathrm{G}$.

### *D. Driving tasks*

As in the previous study [44], a 100 km, two-lane, straight expressway with 3.7 $\mathrm{m}$-wide lanes was used. The participants were required to drive in the left-hand lane. The task was to keep the vehicle at the center of the driving lane while gripping the wheel. To create a monotonous environment, the desired speed of the longitudinal control was set to 100 $\mathrm{km/h}$. In connection with the proposed dual-control scheme, the participants were instructed to take steering action to bring the vehicle back to the center of the lane when they recognized the execution of the first-stage control. In addition, the participants were instructed to consider the accelerator action to return to the normal condition when they recognized the execution of the deceleration control to bring the vehicle to a controlled stop. When the participants stepped on the accelerator while the deceleration control activation, the target speed for longitudinal control was reset to 100 $\mathrm{km/h}$.

### *E. Procedure*

The experimental procedure was very similar to that used in a previous study [44]. The experiment was performed for one day for each participant. All the participants came to the experiment room at 11:30 AM on the specified date. Informed consent was obtained from all the participants. The participants then completed practice runs to familiarize themselves with the driving simulator. In the trial, the participants freely drove using a simulator equipped with the partial driving automation using the proposed dual–control scheme. Consequently, all the participants experienced the operation of the proposed dual–control scheme. Afterward, all the participants were required to take a lunch break between 12:00 and 12:50 and were instructed not to consume caffeine. The calibration for measuring eyelid opening with the Smart Eye camera was conducted between 12:50 and 13:00. The experimental session was scheduled from 13:00 to 14:00. Therefore, at least one and a half hours had passed since the instruction to refrain from caffeine since the beginning of the experimental session. All the participants initiated the experimental session by depressing the accelerator pedal, which activated the partial driving automation system. In this experiment, the temperature of the experiment room was adjusted to approximately 26 °C, which is a temperature known as thermal comfort (thermally neutral) [49], using an air conditioner to maintain a comfortable, drowsiness-inducing environment.

### *F. Measurements and data processing*

The measurement items were recorded with the driving simulator at a sampling frequency of 120 Hz: the time at which the first- and second-stage controls were executed, speed $[\mathrm{km/h}]$, vehicle lateral position $[\mathrm{m}]$, steering angle $[\mathrm{degrees}]$, steering angular velocity $[\mathrm{degrees/s}]$, steering torque input by the drivers $[\mathrm{Nm}]$, steering torque input by the system $[\mathrm{Nm}]$, and accelerator pedal stroke $[\%]$. The distance between eyelids $[\mathrm{mm}]$ and the pitch and roll angles of the head pose $[\mathrm{degrees}]$ were recorded with the Smart Eye camera at a sampling rate of 60 Hz.

*Facial expression:* The arousal state was assessed based on the drowsiness scale [33] every 20 s by three evaluators who assessed the participants' drowsiness level using the criteria listed in Table I. In this experiment, falling asleep indicated level 5 drowsiness. The drowsiness levels were averaged and rounded off for each rating.

*Eyelid activity and head movement:* The preprocessing of the raw data of the distance between the eyelids and head pose directions (pitch and roll angles), such as filtering, was conducted. The distance between the eyelids was normalized to [0, 100], and the value was treated as the degree of eyelid opening. In this study, eyelid closure was defined as eyelid opening less than 20%, and the percentage of eyelid closure time within a 60-second moving window was then calculated.

The data of the eyelid opening and the roll and pitch angles of the head pose were segmented into 20-s sections to evaluate the driver behavior over a short timeframe. The number of blinks per 20 s and the SD of the roll and pitch angles of the head pose per 20 s were calculated.

*Lateral vehicle motion:* The data of the steering torque input by the drivers and the vehicle lateral position were also segmented into 20-s sections. The mean and SD of the driver's input torque per 20 s, and the SD of the lateral position per 20 s were calculated.

### G. Statistical analysis

To verify the hypotheses provided in Section I-B, we investigated the following points:

*1) Influence of the drowsiness level on the driver behavior:* We wished to focus on analyzing how the proposed dual control scheme was activated during which drivers were sleepier. In a comfortable environment (approximately 26 °C) that induces drowsiness in the early afternoon (13:00–14:00), the participants were required to perform the monotonous 60-min driving task using partial driving automation. The symptoms of sleepiness and passive fatigue can be combined over a period of time. In this study, we investigated the influence of drowsiness level on the driver behavior, rather than the influence of elapsed time on the driver behavior. A one–way analysis of variance (ANOVA) was performed to investigate the influence of one categorical independent variable (five-point drowsiness level) on six dependent variables. The dependent variables were the number of blinks $[\mathrm{count}]$, SD of head roll and pitch angles $[\mathrm{degrees}]$, mean and SD of driver torque $[\mathrm{Nm}]$, and SD of the vehicle lateral position $[\mathrm{m}]$. The drowsiness level over a period of time is an uncontrollable factor, and thus, the drowsiness level has an unbalanced sample size across the five levels. First, the dependent variables were sorted according to the drowsiness level for each participant. Then, the mean values of the dependent variables sorted by the drowsiness level were calculated for each participant. In this analysis, the drowsiness level was treated as a within-subject factor. In the ANOVA, if the violation of the sphericity occurred in Mauchly's sphericity test, the Greenhouse–Geisser correction was used to adjust for the lack of sphericity assumption. Post hoc comparisons were performed using Bonferroni correction. For these analyses, the statistical package for social science (SPSS) was used, and we set alpha levels at $p < .01$ to interpret significant results in the ANOVA procedure.

*2) Effectiveness of safety control:* The number of first- and second-stage controls activated across participants was counted and categorized under each drowsiness level. To visualize the effect of lane centering control on the vehicle lateral position, the histograms of the vehicle lateral position for the previous (manual condition [44]) and present (hands-on partial driving automation) studies were compared.

The probable causes of first-stage control activation were investigated. The analysis focuses on the period 5 s immediately before the first-stage control in the approach phase for lane departure. The eyelid opening and percentage of eyelid closure when the system initiated the first-stage control were extracted, and the maximum values of the driver input torque and steering angular velocity in the 5 s were calculated.

The driver response to the first-stage control was also analyzed. The driver reaction time was defined as the time elapsed before the driver performed a steering action or accelerator action after the system implemented the first-stage control, and it was categorized under each drowsiness level. Because of the unbalanced sample size across the five drowsiness levels and the violation of homogeneity of variance, a Kruskal–Wallis rank-sum test was performed, and pairwise comparisons were examined using the Dunn–Bonferroni method.

*3) Effectiveness of driver state identification:* To evaluate the accuracy of the system, four possible outcomes [50] were evaluated: correct, false, missed detections, and correct rejection. In this analysis, facial expression results were used to determine the true state of the participants. A correct detection occurred when the system determined that "the driver failed to supervise the partial driving automation system," when in fact the driver's drowsiness was at level 5. A false detection occurred when the system determined that "the driver failed to supervise the partial driving automation system," when the driver's drowsiness was less than that at level 5. By contrast, a missed detection occurred when the system determined that "the driver had supervised the partial driving automation system" when in fact the driver's drowsiness was at level 5. A correct rejection occurred when the system determined that "the driver had supervised the partial driving automation system," when the driver's drowsiness was less than that at level 5. The accuracy, precision, recall, and specificity were also calculated, respectively.

Finally, the timeliness of the judgments was assessed as the time elapsed before the system judged that "the driver failed to supervise the partial driving automation system" after they reached level 5 of drowsiness for the first time.

## III. RESULTS

Data from 16 of the 20 participants were used in the analysis. We excluded the data from four participants because of the suspension of the experiment due to simulator sickness and a calibration failure to measure their eyelid opening.

### A. Drowsiness and driver behavior

Although individual differences were observed in the tendency to be drowsy, all the participants' drowsiness was rated as level 5 at least once. The total driving time for each drowsiness level across the participants is presented in Table II. As a result of creating a monotonous and comfortable environment, the participants' drowsiness was rated as level 5 for approximately 171 min, which is approximately 17.9 $\%$ of the total driving time (960 min). The statistical descriptions (mean and SD) of the number of blinks $[\mathrm{count}]$, SD of the head roll and pitch angles $[\mathrm{degrees}]$, mean and SD of the driver torque $[\mathrm{Nm}]$, and SD of the vehicle lateral position $[\mathrm{m}]$ are listed in Table III. The results of the one-way ANOVA are summarized in Table IV. In the statistical analyses, data from

TABLE II

TOTAL DRIVING TIME FOR EACH DROWSINESS LEVEL ACROSS PARTICIPANTS

| | | Drowsiness level | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | Total |
| Total driving time | [min] | 72.0 | 159.0 | 275.3 | 281.9 | 171.8 | 960 |
| | [%] | 7.5 | 16.6 | 28.7 | 29.3 | 17.9 | 100 |

TABLE III

DESCRIPTIVE STATISTICAL VALUES FOR DRIVER STATE AND BEHAVIOR.

| | Drowsiness level | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| Number of blinks [count] | 9.83 (2.60) | 10.18 (1.19) | 9.03 (0.99) | 6.05 (0.44) | 3.83 (0.58) |
| SD of head roll angle [degrees] | 0.42 (0.07) | 0.59 (0.07) | 0.82 (0.04) | 0.90 (0.05) | 1.01 (0.12) |
| SD of head pitch angle [degrees] | 0.92 (0.12) | 1.24 (0.19) | 1.87 (0.12) | 1.86 (0.21) | 1.85 (0.33) |
| Mean of driver torque [Nm] | 0.34 (0.07) | 0.34 (0.06) | 0.27 (0.04) | 0.22 (0.02) | 0.22 (0.03) |
| SD of driver torque [Nm] | 0.07 (0.02) | 0.11 (0.01) | 0.14 (0.01) | 0.15 (0.02) | 0.16 (0.04) |
| SD of vehicle lateral position [m] | 0.08 (0.02) | 0.13 (0.02) | 0.12 (0.03) | 0.12 (0.02) | 0.13 (0.05) |

TABLE IV

THE RESULTS OF UNIVARIATE ANALYSIS OF VARIANCE FOR DRIVER STATE AND BEHAVIOR.

| | *df* | *F* | $p$ | Partial $\eta^2$ |
|---|---|---|---|---|
| Number of blinks [count] | 1.09, 15.25 | 86.98 | $<$ **0.01** | 0.86 |
| SD of head roll angle [degrees] | 1.94, 27.24 | 228.51 | $<$ **0.01** | 0.94 |
| SD of head pitch angle [degrees] | 2.04, 28.61 | 145.18 | $<$ **0.01** | 0.91 |
| Mean of driver torque [Nm] | 1.21, 17.02 | 75.53 | $<$ **0.01** | 0.84 |
| SD of driver torque [Nm] | 1.07, 15.02 | 33.12 | $<$ **0.01** | 0.70 |
| SD of vehicle lateral position [m] | 1.53, 21.42 | 23.33 | $<$ **0.01** | 0.62 |

15 participants were used; for one participant, the data under level 1 of drowsiness were not available. The main effect of drowsiness level on these dependent variables was statistically significant ($p < .01$). For the number of blinks, the pairwise comparisons indicated statistically significant differences for all levels except levels 1 and 2 and levels 1 and 3 ($p < .01$). For the SD of the head roll angle, the pairwise comparisons indicated statistically significant differences between all levels ($p < .01$). For the head pitch angle, the pairwise comparisons indicated statistically significant differences between all levels except levels 3 and 4, 3 and 5, and 4 and 5 ($p < .01$). For the mean steering torque input, the pairwise comparisons indicated statistically significant differences between all levels except levels 1 and 2, and levels 4 and 5 ($p < .01$). For the SD of the steering torque input, the pairwise comparisons indicated statistically significant differences between all levels except levels 3 and 5 and levels 4 and 5 ($p < .01$). For the SD of the lateral position, the pairwise comparisons indicated statistically significant differences between levels 1 and 2, 1 and 3, 1 and 4, 1 and 5, and 2 and 3 ($p < .01$).

### B. Safety control performance

Fig. 5 shows the histograms of the lateral position; (a) is the result obtained from the previous study [44] under the manual driving condition and (b) is the result obtained from this study's experiment under the partial driving automation condition. On the horizontal axis, the center of the lane was at 0 m, lane markers were at $\pm 1.85$m, and the desired positions for activating the first-stage control were at $\pm 1.35$ m. This figure reveals that the LCS performance was sufficient (SD = 0.38 (manual) vs. 0.25 (partial driving automation)). In addition, Fig. 5 clearly shows that the lane departure occurrences were prevented by the first-stage control even under partial driving automation condition.

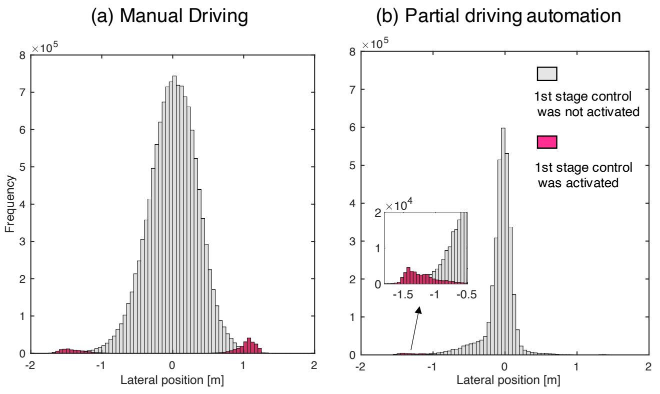

Fig. 5. Histograms of the vehicle's lateral position for (a) manual [44] and (b) partial driving automation conditions. Gray denotes the lateral positions at which the first-stage control was not activated and purple denotes the lateral positions at which the first-stage control was activated.

The total number of safety controls activated across the participants is summarized in Table V. The first-stage control was executed 5, 34, 57, and 33 times under drowsiness levels 2, 3, 4, and 5, respectively. In 123 of the 129 instances in which the first-stage control was implemented (95.3%), the

TABLE V
TOTAL NUMBER OF SAFETY CONTROLS ACTIVATED ACROSS PARTICIPANTS

| | Drowsiness level | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | Total |
| The system implemented the 1st stage control. | 0 | 5 | 34 | 57 | 33 | 129 |
| The system implemented the 2nd stage control. | 0 | 1 | 6 | 11 | 12 | 30 |
| The system brought the vehicle to a complete stop. | 0 | 0 | 0 | 0 | 4 | 4 |

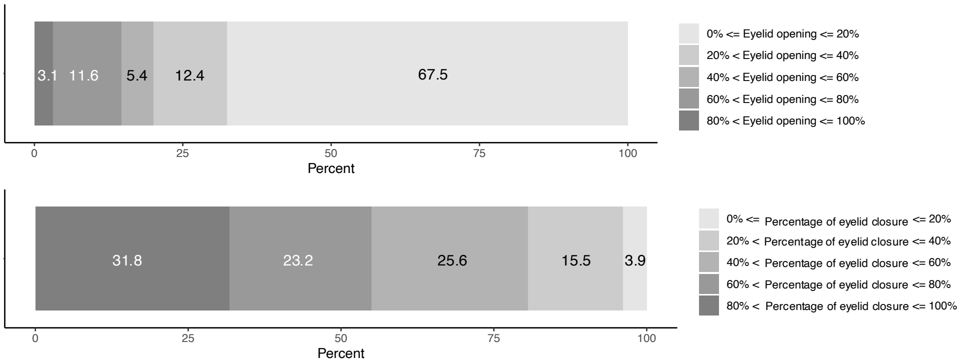

Fig. 6. Classifications of the eyelid opening and percentage of eyelid closure in a 60-second moving window at time when the system initiated the first-stage control.

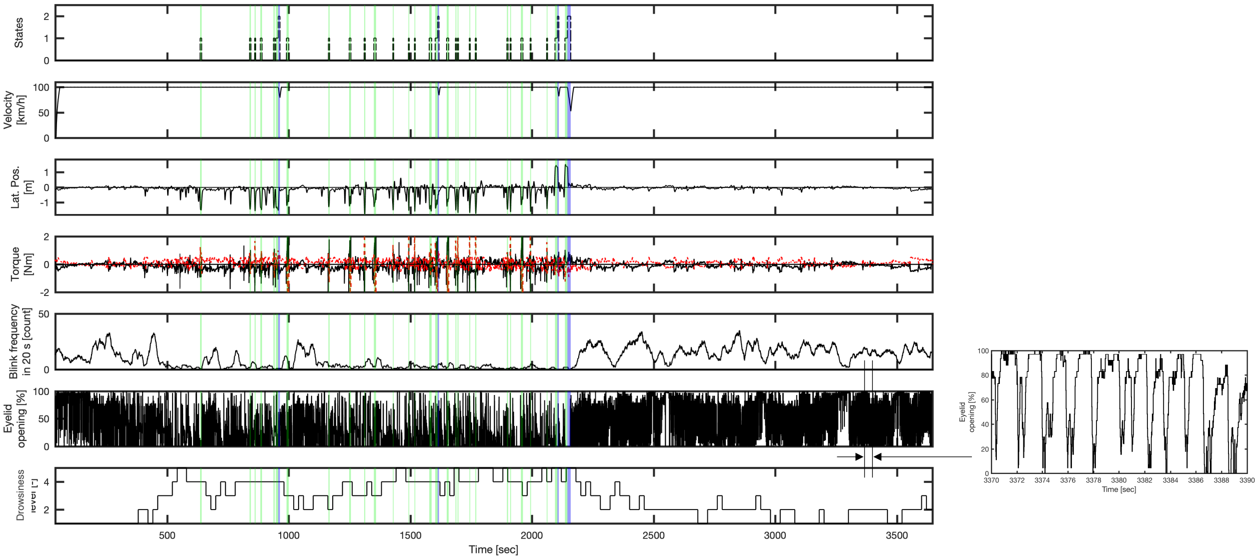

Fig. 7. Time-series data of 3500 s in trial of Participant 18. In the torque data, the red dash line shows assisting torque by the system and the black solid line shows the driver's input torque. The areas shaded in green and blue denote the time interval in which the system executed first- and second-stage control, respectively.

participants' drowsiness levels were between levels 3 and 5. Fig. 6 shows the five classifications for the eyelid opening and percentage of eyelid closure when the system initiated the first-stage control. In 87 of the 129 instances of the first-stage control activation (67.5%), the participants' eyelids were between 0% and 20% open, indicating that control was activated in while the participants' eyelids were closing. In 124 of the 129 instances (96.1%), the participants' percentage of eyelid closure in a 60 s moving window were more than 20%. Of the 129 first-stage control activations, the second-stage control needed to be implemented 1, 6, 11, and 12 times under drowsiness levels 2, 3, 4, and 5, respectively. Thus, in these cases, the deceleration control was activated. In four of the 12 instances (33.3%) in which the second-stage control was implemented under level 5 of driver drowsiness, the system brought the vehicle to a complete stop.

Fig. 7 illustrates the data for 3500 s over the interval [100 s, 3600 s] during the trial of Participant 18. It shows the system states [1: implementing the first-stage control, 2: implementing the second-stage control], lateral position $[\mathrm{m}]$, system's torque $[\mathrm{Nm}]$, driver's torque $[\mathrm{Nm}]$, blink frequency per 20 s [count], eyelid opening $[\%]$, and drowsiness level. The areas shaded

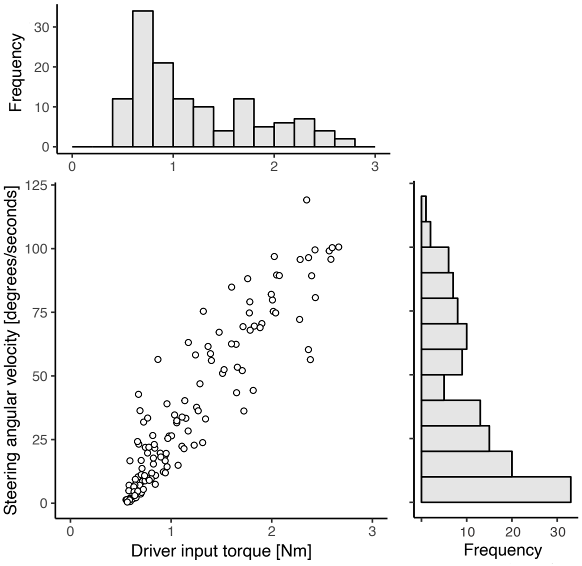

Fig. 8. Inappropriate torque input to the steering wheel.

in green and blue denote the time interval in which the system executed first- and second-stage control, respectively. The blink frequency was visualized by a 20 s moving time window. The eyelid opening data in Fig. 7 confirm that the amount of time that the driver's eyelids were lowered increased in the 1700 s interval [500 s, 2200 s]. A decline in blink-related activities was evident. Drowsiness levels show that the participant's arousal levels were low during this time interval. The system repeatedly performed first-stage control to prevent lane departure and activated second-stage control four times. By contrast, at the time interval from approximately 2500 s to 3600 s, the participant's drowsiness levels ranged between 1 and 3. The torque data in Fig. 7 show clear differences in the participant's torque observed during the two time intervals.

### *C. Probable causes for first-stage control activation*

The probable causes for the activation of the first-stage control were investigated using the drivers' behavior data obtained 5 s immediately before the first-stage control, focusing on the approach toward lane departures. The relationship between the maximum value of the steering angular velocity and the maximum value of the driver's input torque is shown as a scatter plot in Fig. 8. In this experiment, the maximum amount of torque produced by the LCS was set to ± 0.5 Nm. Thus, lane departure occurrence was predicted when the participant inputs a torque of 0.5 Nm or more to the wheel. As can be seen in the histograms of the driver's maximum torque and the maximum steering angular velocity, although the most frequent values fell between 0.6 and 0.8 Nm and between 0 and 10 degrees/s, respectively, both values were widely distributed. This result implies a mixture of several driver behaviors.

A typical example of a participant's inappropriate steering behavior is shown in the time-series data (from Participant 2) in Fig. 9. One graph is for the interval [1050 s, 1150 s], and the other is for the interval [1200 s, 1300 s]. In both cases, the system initiated the first-stage control to prevent lane departure in while the participant's eyelids were closing. In the interval [1050 s, 1100 s], several instances of opening the eyelids were observed. In conjunction with this activity, the torque input to the wheel increased. When the participant inputted an undesirable torque (greater than 0.5 Nm) at approximately 1090 s, the vehicle was clearly going to deviate from the

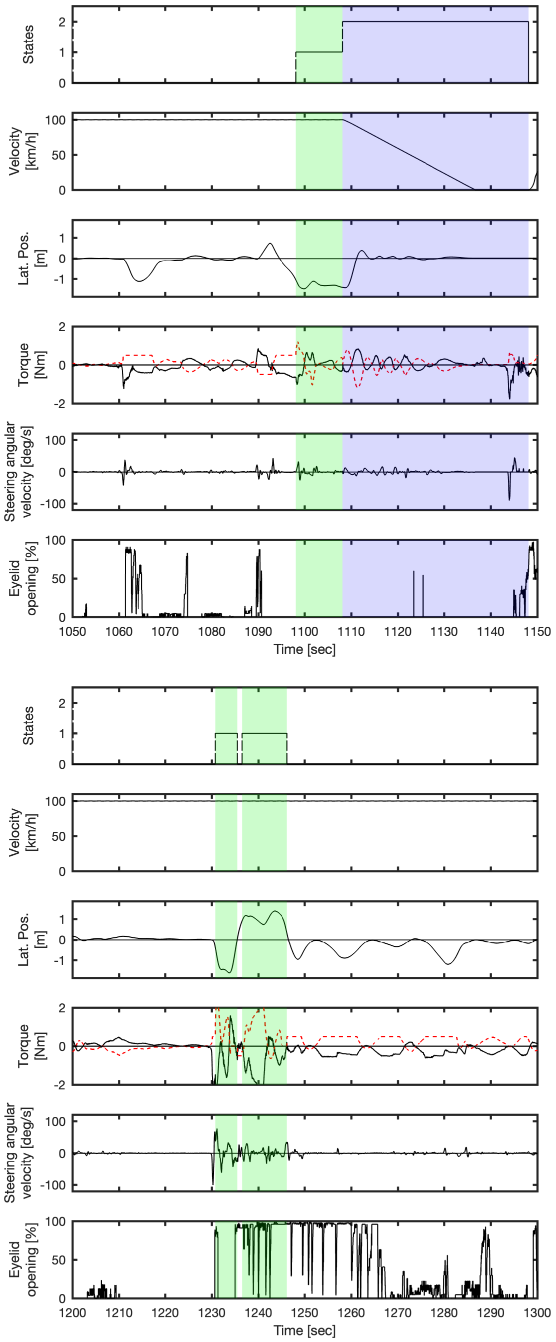

Fig. 9. Time-series data during the trial of Participant 2: The top graph shows the interval [1050 s, 1150 s] and the bottom graph shows the interval [1200 s, 1300 s]. The areas shaded in green and blue denote the time interval in which the system executed first- and second-stage control, respectively. In the torque data, the red dash line shows assisting torque by the system and the black solid line shows the driver's input torque.

TABLE VI
ACCURACY OF DRIVER STATE ESTIMATION

| | | System's judgment | |
|---|---|---|---|
| | | "The driver failed to supervise the partial driving automation system" | "The driver had supervised the partial driving automation system" |
| True state | The driver's drowsiness was at level 5 | 12 | 21 |
| | The driver's drowsiness was less than level 5 | 18 | 78 |

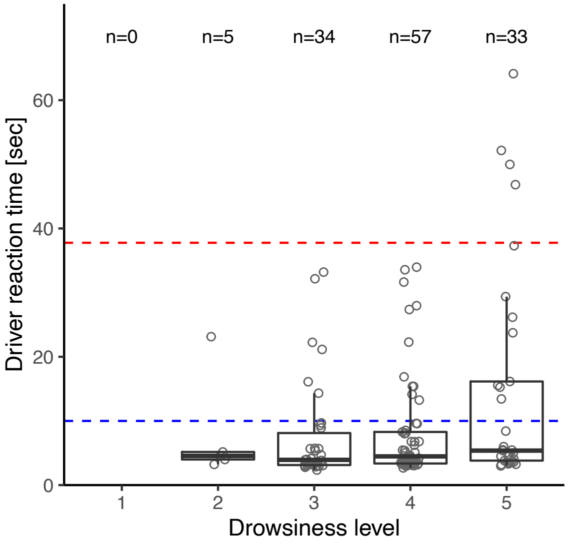

Fig. 10. The time elapsed before the participants performed steering or acceleration actions after the activation of first-stage control. The blue dashed line indicates the time at which the deceleration control was initiated, and the red dashed line shows when the vehicle's speed reached zero $[\mathrm{km/h}]$ through the execution of the deceleration control.

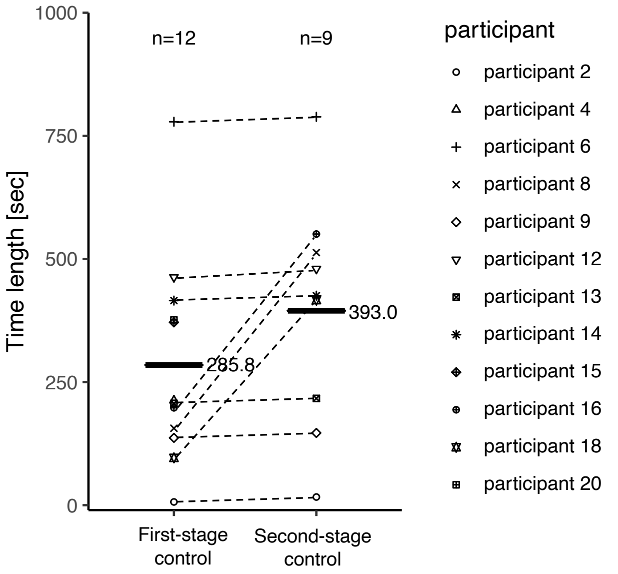

Fig. 11. Time elapsed before the system initiated first- and second-stage control after the drowsiness level reached 5 for the first time.

driving lane. In this event, the system carried out deceleration control and stopped the vehicle in the driving lane because the participant could not perform the proper action after the first-stage control activation.

By contrast, at approximately 1230 $\mathrm{s}$, the participant inputted an undesirable torque to the steering wheel, which was completely different from that in the interval [1050 $\mathrm{s}$, 1150 $\mathrm{s}$]. The maximum value of the angular velocity reached approximately 100 $\mathrm{degrees/s}$. The recorded video confirmed that the balance of the torque applied to the wheel was lost because the participant's hand slipped off the wheel. This type of data was observed in multiple cases, as shown in Fig. 8. Angular velocity exceeding 50 $\mathrm{degrees/s}$ essentially indicates situations in which one of the participants' hands slipped off the wheel because of drowsiness and was not a rare event.

### *D. Driver actions under the activation of first-stage control*

Fig. 10 shows a boxplot for the time elapsed before the participants performed steering or acceleration action after the activation of the first-stage control. The blue dashed line indicates the time at which the deceleration control was initiated, and the red dashed line shows when the vehicle's speed reached zero $[\mathrm{km/h}]$ through the execution of the deceleration control. The median values were 4.5, 3.9, 4.4, and 5.4 $\mathrm{s}$ under drowsiness levels 2, 3, 4, and 5, respectively. The Kruskal–Wallis rank-sum test indicated no significant difference across drowsiness levels ($\chi(3)$ = 5.54, $p = 0.135$). In many cases, the participants recognized first-stage control through haptic feedback and initiated the steering action within 10 s. This result was consistent with that obtained under the manual driving condition [44]. However, as the drowsiness level increased, the percentage of cases in which the driver failed to respond appropriately increased (Table. V).

### *E. Accuracy and timeliness of the system's judgement*

The four possible outcomes of the system's judgement are listed in Table VI. Of the 129 instances in which the first-stage control was activated, correct detection occurred in 12 instances (9.3%), correct rejection in 78 instances (60.5 %), false detection in 18 instances (13.9%), and missed detection in 21 instances (16.3%). Using Table VI, we calculated the system's accuracy, precision, recall, and specificity, which were 0.70, 0.40, 0.36, and 0.81, respectively. Among the 12 instances of correct detection, in four cases, the vehicle was completely stopped in the driving lane through the implementation of the deceleration control. In the 12 cases, the mean time to implement accelerator action after the second-stage control activation was 23.16 $\mathrm{s}$ (SD = 17.01). Among the 18 instances of false detection, in 11 instances (61%), the drivers' drowsiness level was rated as 4. In the false detection cases, the mean time to implement accelerator action after the second-stage control activation was 12.57 s (SD = 7.34). Among the 21 missed detections, in 15 instances (71%), the participants had one hand slipping off the wheel because of drowsiness. In the 21 cases, steering action was implemented at a mean of 4.41 s (SD = 1.27) after the first-stage control activation owing to the improper torque input applied. Among the 78 correct rejection cases, in 46 instances (59%), the drivers' drowsiness level was rated as 4. The time to implement steering action after the first-stage control activation was 4.56 s (SD = 1.93) on average.

Fig. 11 shows the time elapsed before the system initiated first- or second- stage control after the participants' drowsiness level reached 5 for the first time. The label $n$ denotes the number of participants for whom first- or second-stage control was activated while driving. For the second-stage control, the result is the time elapsed before the system determined that "the driver failed to supervise the partial driving automation system" through the driver automation interaction opportunities triggered by the drivers' inappropriate torque input after the participants' drowsiness level reached 5 for the first time. The mean time for initiating the first-stage control was 285.8 s (4.76 min), with a minimum of 6.59 s (0.11 min) and a maximum of 778.6 s (12.97 min). The mean time for initiating the second-stage control was 393.0 s (6.55 min), with a minimum of 16.59 s (0.28 min) and a maximum of 788.6 s (13.14 min).

## IV. DISCUSSIONS

In hands-on automated driving systems (i.e., SAE Level 2 [11]), drivers are expected to complete monitoring tasks via continuous interactions that keep drivers in the loop. However, in a comfortable and monotonous environment, the participants clearly suffer from drowsiness. The statistical analyses revealed substantial differences in the driver behavior across drowsiness levels. As drowsiness levels increased, the frequency with which drivers' head inclined in the roll direction tended to increase, and they tended to input a lower mean torque. The steering torque input by the participants with drowsiness level 4 or higher was significantly less than that of participants with a drowsiness level of 3 or less. Moreover, no significant difference in the SD of the steering torque was found between drowsiness levels 3 and 5 and between 4 and 5. This trend is similar to that of the SD of the head pitch angle of the driver. The SDs of both the driver's steering torque and head pitch angle increased in the process of reaching level 3 of drowsiness. Owing to the increased SD in the steering torque, the SD of the lateral position also increased. However, a significant difference was observed between level 1 and the rest. This observation differs from the results of a previous study [44]. In this experiment, the partial driving automation assisted the participants in implementing actions by keeping the vehicle in the center of the lane, and the LCS was evidently sufficient to keep the vehicle in the lane.

Throughout the recorded driving time (960 min), 129 lane departures were predicted, and first- or second-stage controls were activated. No complete lane departure was observed owing to the execution of safety controls. The probable causes of the predicted lane departures were investigated. From the time interval 5 s immediately before the first-stage control, in the approach phase of a lane departure, the participants inputted inappropriate torque to the wheel due to drowsiness. Surprisingly, the maximum value of the observed steering angular velocity exceeded 120 $\mathrm{degree/s}$ in a case in which one of the participant's hands slipped off the wheel because of drowsiness. As can be seen in the relationship between the drowsiness level and mean driver input torque, the amount of torque input was significantly lowered at levels 4 and 5 of drowsiness. The participants were not able to maintain a light grasp on the wheel while falling asleep. Owing to the hands-off situation and improper torque input, lane departures were predicted. Most importantly, the proposed approach prevented lane departures, even when such a phenomenon occurred. Thus, the creation of an lane departure prevention (LDP) is vital for attaining safety in the context of hands-on partial driving automation.

In the predicted lane departures, the proposed scheme executed partial steering control, which gave the participants a chance to voluntarily perform the action needed. If the participant could not perform the action needed within 10 s, the system determined that "the driver failed to supervise the partial driving automation system" and executed a strategy to bring the vehicle to the controlled stop. To evaluate the effectiveness of the driver state identification, we considered four possible outcomes for the system's judgment: correct, false, missed detections, and correct rejection. The accuracy, i.e., the ratio of the sum of the correct detection and correct rejection for the total number of cases, was 0.70. The number of correct rejections was the highest among the four possible outcomes. Among the 129 instances in which the first-stage control was initiated, in 96 times (74.4 %), the participants' drowsiness levels were all lower than level 5. This result could be related to the significant increase in the SD of the steering torque. In many cases, the participants could implement the proper action, and the system determined that "the driver had supervised the partial driving automation." These unsafe behaviors were a prelude to extreme drowsiness. Of the correct detections, in four instances in which participants fell asleep completely, the vehicle was brought to a complete stop. When the participants fell asleep completely while driving, they could not take proper action. However, the precision and recall were 0.40 and 0.36, respectively. Thus, the numbers of false and missed detections were greater than that of correct detections. The missed detections were attributed to cases in which the participants' hands left the wheel, producing an improper torque input. As shown in the time elapsed before the system initiated first- and second-stage control after the drowsiness level reached 5 for the first time (Fig. 11), the result mainly comes from the fact that the drivers' drowsiness level and controller activation have indirect links. In these hands-off cases, the participants whose drowsiness had reached level 5 were immediately aware of the situation due to their behavior. Thus, the participants could perform a steering action to bring the vehicle back into the driving lane. Although the system could prevent lane departures, the occurrence of this situation is undesirable. This issue is related to the timeliness of drowsy driving detection. The time needed for drowsiness detection widely varied, i.e., 0.28–13.14 min. In the experiment, the lane centering system always provided steering assistance to compensate for the drivers' steering action in the range of $\pm 0.5\ \mathrm{Nm}$. In the context of manual driving, letting go of the steering wheel completely, producing improper torque input, is unlikely. Normally, a lane departure would occur before such a situation could be triggered. However, because partial automation balanced the driver and system torque, there were some cases where the driver state was not identified at an early stage. To reduce the missed detections that occurred when the driver's hands left the wheel, we should identify the driver state at an earlier stage. Moreover, the steering torque input by the significantly or extremely drowsy participants was very small. Thus, deviations from normality may be determined using the driver's torque information. Furthermore, the number of false detections may be due to inaccurate classification based on the subjective rating of driver drowsiness. This was because we observed several cases where the driver was not able to quickly respond to the situation by stepping on the accelerator pedal, even when their drowsiness level was rated as 3 or 4 (Fig. 10). In this analysis, although the facial expression results were used to determine the true state of the participant, the objective verification of driver state identification that does not rely on subjective ratings is necessary.

The present study applied the proposed dual-control scheme to hands-on partial driving automation. We found that in drowsy driving, in which participants' eyelids were completely closed and their heads frequently inclined in the directions of roll and pitch angles, they inputted inappropriate torque to the wheel. When the participants fell asleep, they could not maintain a light grasp on the wheel, leading to a hands-off situation with an improper torque input. The proposed approach prevented lane departures and deemed that "the driver failed to supervise the partial driving automation system," essentially supporting the hypotheses. Nonetheless, the findings of this study should be considered with the following limitations: The dual-control scheme was a useful mechanism to avoid lane departures and to create driver-automation interaction opportunities, even under hands-on partial driving automation. However, we need to enhance the driver state estimation to identify the driver state at an earlier stage. In this experiment, the maximum amount of torque assisted by the LCS was set to $\pm 0.5\ \mathrm{Nm}$ because drivers must be in command of their driving owing to the system's limited ability. If the system is more capable of supporting lane centering, then fewer lane departures that trigger action and investigation would occur. A driver monitoring approach based on the combination of the dual-control scheme and direct driver-related measures should be considered in future studies. Although this study was focused on using steering signals for safety control and real-time identification, deceleration control signals can also be effective for these goals. The proposed scheme, which also utilizes direct driver-related measures, can execute the first-stage control in a timely and effective manner. Although the driver response was observed repeatedly over a period of time, the driver drowsiness and response over a period of time were not considered in testing the hypotheses because the symptoms of sleepiness and passive fatigue can co-occur, which makes it difficult to separate the underlying mechanisms with the method used in this study. In addition to the objective verification of driver state identification, an analysis approach that incorporates the repeated nature of dependent measures for each participant over time should be considered. This study assumed that the road is straight, but the possibility of lane departure accidents may be high along the curves. Therefore, the control algorithm should be improved for it to be applied to more complex situations. In this experiment, when the predicted value of the time margin for lane departure became less than $1\ \mathrm{s}$, the system initiated the first-stage control. Generally, drivers have a boundary of acceptable limits within which they operate [51]. The safety margin that can effectively trigger the first-stage control should also be explored in the context of partial driving automation. To bring the vehicle to a complete stop, the vehicle can be stopped in the driving lane or it can be pulled over and stopped on the side of the road. The choice of strategy depends on the road traffic context as well as the driving automation's capability for sensing the surroundings to localize the vehicle's position. When the vehicle is running in the lane adjacent to the shoulder of the road, stopping on the shoulder may be done in a straightforward manner. On the other hand, if the vehicle was running in the passing lane, automatic lane change maneuvers would be required to bring the vehicle to the shoulder for a complete stop, especially when the driver fails to respond to the situation. If it was hard to be sure of the driving automation's capability for sensing the surroundings, it may be one of realistic options to make the vehicle stop on the currently driving lane while giving some emergency notifications to the surrounding vehicles. However, this may involve risks associated with rear-end collisions with other vehicles. Thus, stopping a vehicle in the lane should be the last resort, and the capacity to encourage drowsy drivers to stop driving at an early stage is needed. As previously described, our experiment simulated a 100 km, two-lane, straight expressway. Our research is limited by the constraints of the fixed-base simulator environment. Such investigations have limited physical, perceptual, and behavioral fidelity [52], [53]. Käppler [53] has pointed out that the lack of real danger in driving simulators can induce a false sense of safety, responsibility, or competence. Hence, further studies are necessary to investigate whether drivers will accept the system's behavior in a more realistic driving context.

## V. CONCLUSIONS

This study examined the effectiveness of a dual-control scheme to identify the driver drowsiness and bring the vehicle to a controlled stop. The proposed system executed a first-stage control (partial steering control) when it anticipated a vehicle lane departure and then activated deceleration control if the driver could not perform the required action properly (and failed to respond to the partial steering control). To determine whether the driver is supervising partial driving automation, the proposed system attempted to create an opportunity for driver–automation interactions in the context of hands-on partial driving automation. This study aimed to demonstrate the feasibility of the proposed system using only vehicle information. In a sleep-inducing environment, a fixed-base driving simulator experiment was designed to investigate the effectiveness of the dual control scheme in identifying driver drowsiness and preventing lane departures. For driver monitoring via the proposed system, the accuracy, precision, recall, and specificity were 0.70, 0.40, 0.36, and 0.81, respectively. While we observed cases in which the system could effectively bring the vehicle to a controlled stop through the driver–automation interaction opportunities via the dual-control scheme, the timeliness and accuracy of the driver state identification remained as issues owing to indirect links between the drivers' drowsiness level and controller activation. Although the dual-control scheme is a useful mechanism to avoid lane departures and to create driver-automation interaction opportunities even under hands-on partial driving automation, the driver state identification needs to be improved to ensure timely and effective detection of driver drowsiness. Thus, in future works, it should be paired with a direct driver-related measurement system. More research is needed, and we encourage further exploration of cooperative interactions between humans and machines.

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## REFERENCES

[1] M. Körber, A. Cingel, M. Zimmermann, and K. Bengler, "Vigilance decrement and passive fatigue caused by monotony in automated driving," *Procedia Manufacturing*, vol. 3, pp. 2403–2409, 2015, 6th International Conference on Applied Human Factors and Ergonomics (AHFE 2015) and the Affiliated Conferences, AHFE 2015.

[2] M. Hjälmdahl, S. Krupenia, and B. Thorslund, "Driver behaviour and driver experience of partial and fully automated truck platooning –a simulator study," *European Transport Research Review*, vol. 9, no. 1, pp. 1–11, 2017.

[3] C. Ahlström, R. Zemblys, H. Jansson, C. Forsberg, J. Karlsson, and A. Anund, "Effects of partially automated driving on the development of driver sleepiness," *Accident Analysis & Prevention*, vol. 153, p. 106058, 2021.

[4] J. F. May and C. L. Baldwin, "Driver fatigue: The importance of identifying causal factors of fatigue when considering detection and countermeasure technologies," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 12, no. 3, pp. 218–224, 2009.

[5] J. C. Verster and T. Roth, "Vigilance decrement during the on-the-road driving tests: The importance of time-on-task in psychopharmacological research," *Accident Analysis & Prevention*, vol. 58, pp. 244–248, 2013.

[6] P. Thiffault and J. Bergeron, "Monotony of road environment and driver fatigue: a simulator study," *Accident Analysis & Prevention*, vol. 35, no. 3, pp. 381–391, 2003.

[7] G. S. Larue, A. Rakotonirainy, and A. N. Pettitt, "Driving performance impairments due to hypovigilance on monotonous roads," *Accident Analysis & Prevention*, vol. 43, no. 6, pp. 2037–2046, 2011.

[8] D. J. Saxby, G. Matthews, E. Hitchcock, J. Warm, G. J. Funke, and T. Gantzer, "Effect of active and passive fatigue on performance using a driving simulator," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 52, pp. 1751–1755, 2008.

[9] D. J. Saxby, G. Matthews, E. M. Hitchcock, and J. S. Warm, "Development of active and passive fatigue manipulations using a driving simulator," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 51, no. 18, pp. 1237–1241, 2007.

[10] D. Davenne, R. Lericollais, P. Sagaspe, J. Taillard, A. Gauthier, S. Espié, and P. Philip, "Reliability of simulator driving tool for evaluation of sleepiness, fatigue and driving performance." *Accident Analysis & Prevention*, vol. 45, pp. 677–682, Mar 2012.

[11] S. of Automotive Engineers, "Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles (surface vehicle recommended practice: Superseding j3016)," SAE International, Tech. Rep., April 2021.

[12] J. A. Michon, *A Critical View of Driver Behavior Models: What Do We Know, What Should We Do?* Springer US, 1985, pp. 485–524.

[13] T. Motors, "Model s owner's manual," Accessed date: 6 April 2020. [Online]. Available: https://www.tesla.com/sites/default/files/model_s_owners_manual_north_america_en_us.pdf

[14] Cadillac, "Ct6 super cruisetm convenience & personalization guide," Accessed date: 6 April 2020. [Online]. Available: https://www.cadillac.com/content/dam/cadillac/na/us/english/index/ownership/technology/supercruise/pdfs/2019-cad-ct6-supercruise-personalization.pdf

[15] Nissan, "Enhance your journey with propilot 2.0," Accessed date: 6 April 2020. [Online]. Available: https://global.nissannews.com/ja-JP/releases/release-3cbd354e83fc82251bca10fced007427/images/1bd923c83798903cff975b4a585fb5347eccc896

[16] D. A. Abbink, M. Mulder, and E. R. Boer, "Haptic shared control: smoothly shifting control authority?" *Cognition, Technology & Work*, vol. 14, no. 1, pp. 19–28, 2012.

[17] V. A. Banks, A. Eriksson, J. O'Donoghue, and N. A. Stanton, "Is partially automated driving a bad idea? observations from an on-road study," *Applied Ergonomics*, vol. 68, pp. 138–145, 2018.

[18] M. R. Endsley, "Autonomous driving systems: A preliminary naturalistic study of the tesla model s," *Journal of Cognitive Engineering and Decision Making*, vol. 11, no. 3, pp. 225–238, 2017.

[19] N. H. Traffic and S. Administration. Odi resume. [Online]. Available: https://static.nhtsa.gov/odi/inv/2016/INCLA-PE16007-7876.PDF

[20] HAVEit, "The future of driving," Tech. Rep. Deliverable D61.1 Final Report, 2011.

[21] C. Papadelis, Z. Chen, C. Kourtidou-Papadeli, P. D. Bamidis, I. Chouvarda, E. Bekiaris, and N. Maglaveras, "Monitoring sleepiness with on-board electrophysiological recordings for preventing sleep-deprived traffic accidents," *Clinical Neurophysiology*, vol. 118, no. 9, pp. 1906–1922, 2007.

[22] F. Lin, L. Ko, C. Chuang, T. Su, and C. Lin, "Generalized eeg-based drowsiness prediction system by using a self-organizing neural fuzzy system," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 59, no. 9, pp. 2044–2055, 2012.

[23] M. Patel, S. Lal, D. Kavanagh, and P. Rossiter, "Applying neural network analysis on heart rate variability data to assess driver fatigue," *Expert Systems with Applications*, vol. 38, no. 6, pp. 7235–7242, 2011.

[24] M. Itoh, H. Nagasaku, and T. Inagaki, "Analyses of driver's body movement for detection of hypovigilance due to non-driving cognitive task," *IFAC Proceedings Volumes*, vol. 39, no. 12, pp. 644–648, 2006.

[25] J. C. Popieul, P. Simon, and P. Loslever, "Using driver's head movements evolution as a drowsiness indicator," in *IEEE IV2003 Intelligent Vehicles Symposium. Proceedings (Cat. No.03TH8683)*, 2003, pp. 616–621.

[26] A. Mittal, K. Kumar, S. Dhamija, and M. Kaur, "Head movement-based driver drowsiness detection: A review of state-of-art techniques," in *2016 IEEE International Conference on Engineering and Technology (ICETECH)*, March 2016, pp. 903–908.

[27] E. Vural, M. Cetin, A. Ercil, G. Littlewort, M. Bartlett, and J. Movellan, "Drowsy driver detection through facial movement analysis," in *Human–Computer Interaction*, M. Lew, N. Sebe, T. S. Huang, and E. M. Bakker, Eds. Springer Berlin Heidelberg, 2007, pp. 6–18.

[28] M. L. Jackson, S. Raj, R. J. Croft, A. C. Hayley, L. A. Downey, G. A. Kennedy, and M. E. Howard, "Slow eyelid closure as a measure of driver drowsiness and its relationship to performance." *Traffic Inj Prev*, vol. 17, no. 3, pp. 251–257, 2016.

[29] M. Ingre, T. Åkerstedt, B. Peters, A. Anund, and G. Kecklund, "Subjective sleepiness, simulated driving performance and blink duration: examining individual differences," *Journal of Sleep Research*, vol. 15, no. 1, pp. 47–53, 2006.

[30] D. F. Dinges and R. Grace, "Perclos: A valid psychophysiological measure of alertness as assessed by psychomotor vigilance (no. fhwa-mcrt-98-006)," US Department of transportation: Federal Highway Administration, 1998.

[31] B. Mandal, L. Li, G. S. Wang, and J. Lin, "Towards detection of bus driver fatigue based on robust visual analysis of eye state," *IEEE Trans. Intell. Transport. Sys.*, vol. 18, no. 3, pp. 545–557, 2017.

[32] T. Åkerstedt and M. Gillberg, "Subjective and objective sleepiness in the active individual," *International Journal of Neuroscience*, vol. 52, no. 1-2, pp. 29–37, 1990.

[33] H. Kitajima, N. Numata, K. Yamamoto, and Y. Goi, "Prediction of automobile driver sleepiness : 1st report, rating of sleepiness based on facial expression and examination of effective predictor indexes of sleepiness [in japanese]," *Transactions of the Japan Society of Mechanical Engineers Series C*, vol. 63, no. 613, pp. 3059–3066, 1997.

[34] S. Hachisuka, K. Ishida, T. Enya, and M. Kamijo, "Facial expression measurement for detecting driver drowsiness," in *Engineering Psychology and Cognitive Ergonomics*, ser. Lecture Notes in Computer Science, vol 6781, 2011, pp. 135–144.

[35] J. Schmidt, C. Braunagel, W. Stolzmann, and K. Karrer-Gauß, "Driver drowsiness and behavior detection in prolonged conditionally automated drives," in *2016 IEEE Intelligent Vehicles Symposium (IV)*, 2016, pp. 400–405.

[36] W. W. Wierwille and L. A. Ellsworth, "Evaluation of driver drowsiness by trained raters." *Accident Analysis & Prevention*, vol. 26, no. 5, pp. 571–81, 1994.

[37] W. A. Macdonald and E. R. Hoffmann, "Review of relationships between steering wheel reversal rate and driving task demand," *Human Factors*, vol. 22, no. 6, pp. 733–739, 1980.

[38] S. Otmani, T. Pebayle, J. Roge, and A. Muzet, "Effect of driving duration and partial sleep deprivation on subsequent alertness and performance of car drivers," *Physiology & Behavior*, vol. 84, no. 5, pp. 715–724, 2005.

[39] S. Hu and G. Zheng, "Driver drowsiness detection with eyelid related parameters by support vector machine," *Expert Systems with Applications*, vol. 36, no. 4, pp. 7651–7658, 2009.

[40] S. Samiee, S. Azadi, R. Kazemi, A. Nahvi, and A. Eichberger, "Data fusion to develop a driver drowsiness detection system with robustness to signal loss," *Sensors (Basel)*, vol. 14, no. 9, pp. 17 832–17 847, 2014.

[41] D. A. Abbink, T. Carlson, M. Mulder, J. C. F. de Winter, F. Aminravan, T. L. Gibo, and E. R. Boer, "A topology of shared control systems—finding common ground in diversity," *IEEE Transactions on Human-Machine Systems*, vol. 48, no. 5, pp. 509–525, 2018.

[42] K. A. Brookhuis, D. de Waard, B. Peters, and E. Bekiaris, "Save: System for detection of driver impairment and emergency handling," *IATSS research*, vol. 22, no. 2, pp. 37–42, 1998.

[43] P. Hancock and W. Verwey, "Fatigue, workload and adaptive driver systems," *Accident Analysis & Prevention*, vol. 29, no. 4, pp. 495–506, 1997.

[44] Y. Saito, M. Itoh, and T. Inagaki, "Driver assistance system with a dual control scheme: Effectiveness of identifying driver drowsiness and preventing lane departure accidents," *IEEE Transactions on Human-Machine Systems*, vol. 46, no. 5, pp. 660–671, 2016.

[45] A. A. Feldbaum, "Theory of dual control (i)," *Automation and Remote Control*, vol. 21, no. 9, pp. 1240–1249, 1960.

[46] N. M. Filatov and H. Unbehauen, *Adaptive Dual Control: Theory and Applications*. Springer-Verlag Berlin Heidelberg, 2004.

[47] Y. Saito, M. Itoh, and T. Inagaki, "Effects of driver drowsiness on driving performance in the context of partial driving automation requiring hands-on-wheel," in *2020 IEEE International Conference on Human-Machine Systems (ICHMS)*, 2020, pp. 1–4.

[48] F. Naujoks, S. Höfling, C. Purucker, and K. Zeeb, "From partial and high automation to manual driving: Relationship between non-driving related tasks, drowsiness and take-over performance," *Accident Analysis & Prevention*, vol. 121, pp. 28–42, 2018.

[49] I. O. for Standardization, *ISO7730: Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*. International Organization for Standardization: Geneva, Switzerland, 2005.

[50] R. Parasuraman, P. A. Hancock, and O. Olofinboba, "Alarm effectiveness in driver-centred collision-warning systems," *Ergonomics*, vol. 40, no. 3, pp. 390–399, 1997.

[51] E. R. Boer, "Satisficing curve negotiation: Explaining drivers' situated lateral position variability," *IFAC-PapersOnLine*, vol. 49, no. 19, pp. 183–188, 2016.

[52] J. de Winter and R. Happee, "Advantages and disadvantages of driving simulators: A discussion," in *Proceedings of Measuring Behavior 2012*, 2012, pp. 47–50.

[53] W. Käppler, "Views on the role of simulation in driver training," in *Proceedings of the 12th European Annual Conference on Human Decision Making and Manual Control*, 1993, pp. 5.12–5.17.

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