Journal of Research and Applications in Mechanical Engineering
ISSN: 2229-2152 (Print); 2697-424x (Online)
(2023) Vol. 11, No. 2, Paper No. JRAME-23-11-009
[DOI: 10.14456/jrame.2023.9]

Research Article

Evaluation Methods Using Electrodermal Activity for Interface Design of Autonomous Vehicles

K. Miyakawa Weerakoon
D. Misaki*
Department of Mechanical Systems Engineering, School of Engineering, Kogakuin University Shinjuku Campus, Tokyo 163-8677, Japan

Received 20 January 2023
Revised 14 April 2023
Accepted 2 May 2023

Abstract:
Studies on human behavior in automated vehicles and advanced vehicle control are required as automated driving is expected to become more widespread. For example, Level 2 automated vehicles require constant monitoring to ensure the driver takes appropriate action in an emergency, even when driving hands-free. Constant monitoring will likely lead to stress and mental fatigue in the driver. However, proposing a human interface suitable for automated vehicles may reduce the driver's mental fatigue. Evaluation methods are crucial for optimal interface development. In this study, we examined the effectiveness of biological responses and a questionnaire to detect the psychological manner in which drivers of automated vehicles use a driving simulator. The measurement results of the subjects mental fatigue obtained using the questionnaire and 0.05 to 0.6 μS as SCR response amplitudes showed that moving up from Level 1 to 2 of automated driving does not necessarily decrease the driver's mental load.

Keywords: *Autonomous vehicle, User acceptance, Electrodermal activity, Mind perception, Safety introduction*

1. Introduction

In recent years, vehicles equipped with driver assistance and automated driving features have proliferated rapidly, and this trend is expected to continue to increase. However, accidents occurred in self-driving vehicles in 2018. A self-driving car hit and killed a 49-yearold pedestrian crossing the roadway while pushing his bicycle at approximately 64 km/h in Arizona while driving automatically. This fatal accident was the world's first pedestrian fatality in automated driving. Given the possibility of such accidents, there is a need for automated driving to investigate the advanced control of automobiles and human behavior. [1] Several studies on proposals for new out-of-the-box interfaces that consider the coordination between people and cars have been conducted. [2-4] In addition, it is difficult for an automated vehicle to rapidly and appropriately return to manual operation from a nondriving state. In some cases, this can result in accidents. [5] For this reason, research has been conducted on variable steering systems to communicate the state of automatic driving and the state in which a person should take over driving through an easy-to-see interface. [6] Various interfaces have been developed for the automotive industry. [7] However, some hazards and issues still need to be addressed. In vehicles equipped with Level 2 or 3 automated driving functions, the physical workload is reduced because the driver's operation decreases during automated driving. In contrast, fatigue includes both mental and physical fatigue. When hands-free driving is applied, the driver must monitor the situation, which does not necessarily reduce mental fatigue. The mental strain of monitoring the surroundings during automated driving is different from that during manual driving, and in some cases, this mental strain may lead to danger. Therefore, the mental load on drivers and the degree to which they trust selfdriving vehicles have been investigated.

* Corresponding author: D. Misaki
E-mail address: misaki@cc.kogakuin.ac.jp

[8-10] In addition, research has been conducted on improving the reliability of self-driving cars through conversational interfaces. [11] However, these studies used self-reported questionnaires to measure the driver load but did not use real-time quantitative evaluation methods. Studies have also measured trust in self-driving cars based on driver behavior. [12-14] these studies measured trust based on human behavior, and other methods, such as biometric signals, are required to evaluate the mental load. A method using electrodermal activity as a biometric signal has been developed to analyze the mental load and emotions during driving. [15, 16] electrodermal activity refers to the electrical changes measured on the skin surface when the skin receives nerve control signals from the brain. With emotional activation and increased cognitive workload, the brain transmits signals to the skin to increase sweating. This signal change cannot be consciously controlled but is constantly regulated by the body. Several studies have been conducted on electrodermal activity detection during automatic driving. [17] A study investigated the effects of automated driving on people with health concerns. [18] The researchers investigated the driver's trust in fully automated vehicles using questionnaires and electrodermal activity. These studies have shown that the greater the driver's anxiety and mental load, the greater the electrodermal activity value. Thus, electrodermal activity can be used as an evaluation method when designing interfaces for Levels 2 and 3 automated vehicles, where cooperation between the driver and the automated vehicle is vital. The aim of this study was to develop a new evaluation method to propose appropriate interfaces for Levels 2 and 3 automated vehicles through experiments using a driving simulator. Experiments on electrodermal activity measurements and questionnaire surveys were conducted on a driving simulator replicating advanced levels 2 and 1 to detect and compare drivers' mental fatigue during automated driving. Based on the results, we examined the effectiveness of the proposed method as an evaluation method for designing interfaces for automated vehicles to reduce drivers' mental fatigue.

2. Development of Evaluation Method for Interface Design for Levels 2 and 3 Automated Vehicles

The Society of Automotive Engineers (SAE) is engaged in developing automotive and aerospace industry standards. SAE defines the levels of automated driving. [19] Table 1 lists the roles of the driver for each level, as defined by SAE.

Table 1: Levels of Driving Automation [19]

<table>
<tr><th>SAE Level</th><th>Execution of Steering and Acceleration/Deceleration</th><th>Monitoring of Driving Environment</th><th>Fallback Performance of Dynamic Driving Task</th></tr>
<tr><td>0</td><td>Human Driver</td><td rowspan="3">Human Driver</td><td rowspan="4">Human Driver</td></tr>
<tr><td>1</td><td>Human Driver and System</td></tr>
<tr><td>2</td><td rowspan="4">System</td></tr>
<tr><td>3</td><td rowspan="3">System</td></tr>
<tr><td>4</td><td rowspan="2">System</td></tr>
<tr><td>5</td></tr>
</table>

As listed in Table 1, Levels 1–3 automated vehicles require drivers to monitor their surroundings and respond to emergencies. However, this is challenging for drivers. Therefore, it is necessary to develop an interface suitable for a new role in designing a safe car. It is crucial to evaluate it from several perspectives in proposing a safe interface.
In this study, we focused on using a questionnaire and the electrodermal activity, a biometric signal, to measure drivers' mental fatigue. We used the E4 wristband, a biometric device sold by Empatica, to measure the electrodermal activity.

In the experiment, the driver was hands-free in a Level 2 car, and mental fatigue was measured when a possibility of driving takeover existed. Based on the measurement and analysis of the mental demands of drivers using the questionnaire and electrodermal activity, the proposed approach can be utilized for designing systems and interfaces with less mental burden in automated vehicle design.

3. Simulation of Automated Driving Conditions Using Driving Simulator

In the driving simulator used in this study, adaptive cruise control (ACC) was applied using a computer, and lane-keeping assistant (LKA) was controlled using a wizard of OZ prototyping, in which a human operator operated the vehicle out of sight of the subject, to replicate the automatic driving function. [20] ACC is a driving support function in which a machine performs the acceleration and braking operations, and the LKA is a driving support function in which a machine operates the steering wheel. The wizard of OZ prototyping made it possible to conduct an automatic driving experiment relatively rapidly and at a low cost. The simulator consisted of a subject side, a display for replicating automatic driving, and a controller. Unity was used as the driving simulation system. The Vehicle Physics Pro software, available in the unity asset store, was used. [21] The system diagram of the driving simulator system is shown in Fig. 1. Driving simulator devices are shown in Fig. 2.

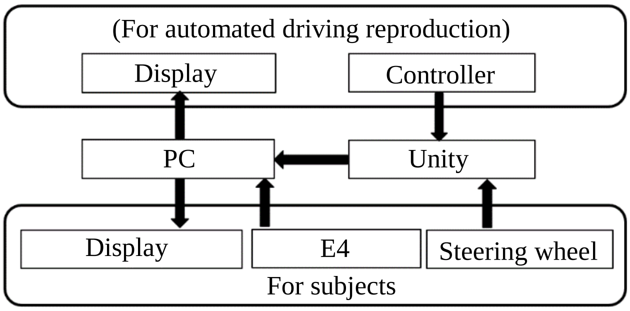

Fig. 1. System diagram of driving simulator

(a) (b)

Fig. 2. (a) Device for subject (b) Device for automated driving

4. Experiment

SAE Level 1 and SAE Level 2 automated driving were replicated using a driving simulator and the wizard of the OZ method. We measured the driver's electrodermal activity during the experiment and administered a questionnaire afterwards. The questionnaire included items on "Mental Demand," "Physical Demand," "Temporal Demand," "Effort," "Performance," and "Frustration" on an 11-point Likert scale. In Level 2 automated driving, the driver must constantly monitor the surrounding environment, even in a handsfree state. In this experiment, a car veered out of its lane during Level 2 driving. When the car strayed out of its lane, the subject took over the driving and moved back into the lane. This placed pressure on the subjects. The following is a detailed description of the experiment.

(1) Experiment 1: Driving experiment of Level 1 degree car

In this experiment, the subjects drove the simulator of a Level 1 vehicle. The ACC was activated as a driving support function, and the speed was automatically maintained at 60 km/h. The subject was only allowed to operate the steering wheel, and the car was driven at 60 km/h. The subject drove the car for 15 min using only a steering wheel.

(2) Experiment 2: Driving experiment of Level 2 car

In this experiment, the subjects drove a simulator of a Level 2 vehicle. The car automatically maintained driving in its lane at 60 km/h with ACC and LKA as automatic driving functions. While driving, the subjects monitored the vehicle to check whether it was moving within its lane. If the car veered out of its lane, the subject took over the driving, manually returned the car to its lane, and then pressed a lever behind the steering wheel to return to automatic driving. In this experiment, the car veered out of its lane three times in 15 min. The time values when the car moved out of its lane were set to 2, 5, and 10 min after the experiment commenced. Six subjects (A, B, C, D, E, and F) aged 22–23 years participated in the experiment. Figure 3 shows the image and driving screen every 4 s from the beginning of lane departure until the driver intervenes and returns to the lane.

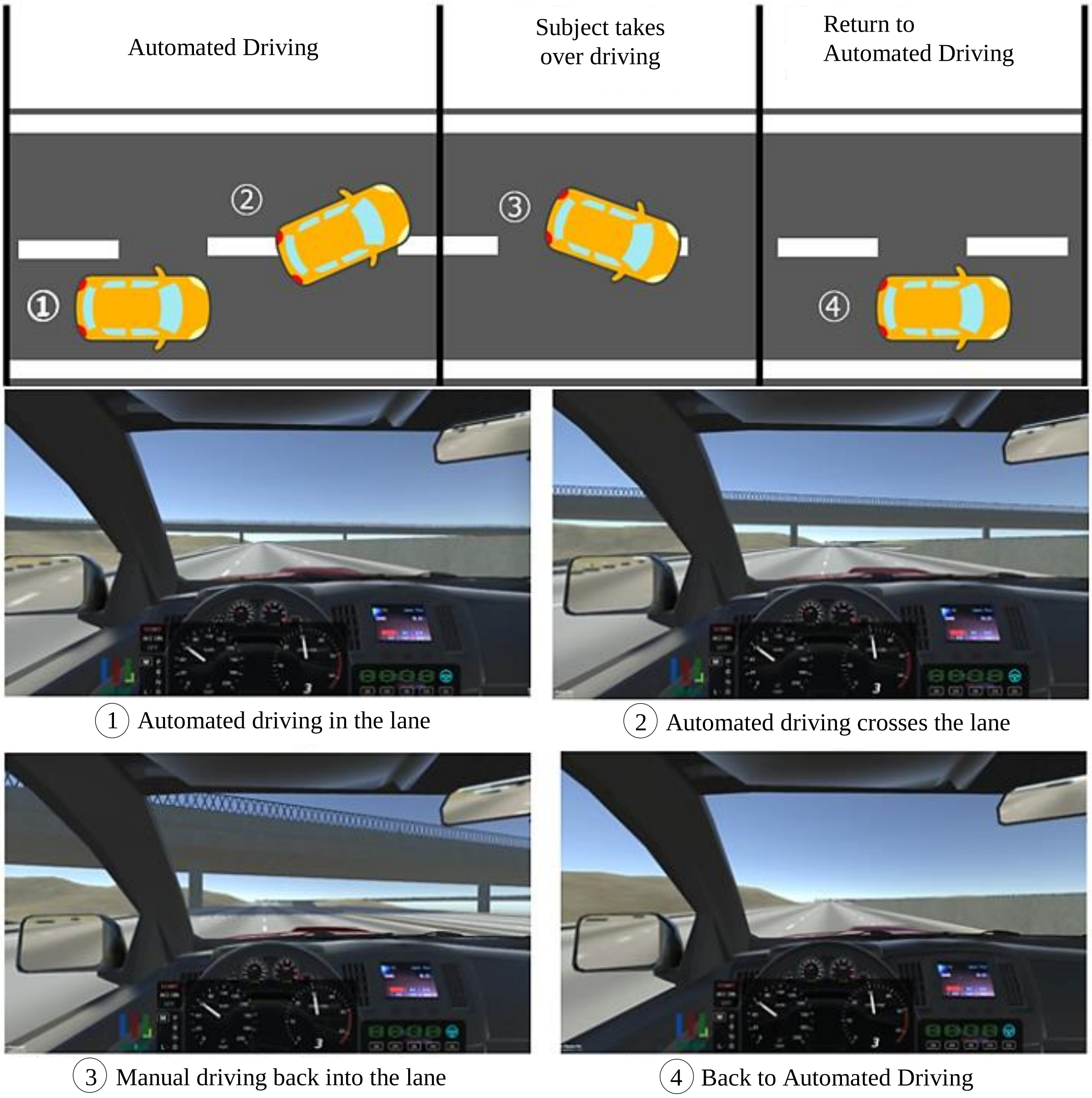

Fig. 3. Procedures for subject's driving intervention

5. Experimental Results

In this experiment, we observed the electrodermal activity changes of subjects whose responses were significant. Figure 4 shows the electrodermal activity change of Subject A while driving a car at approximately Level 1, and Fig. 5 shows the electrodermal activity change of Subject A while driving a car at approximately Level 2.

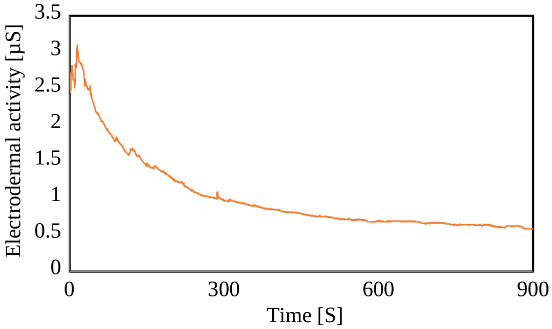

Fig. 4. Electrodermal activity of during Level 1 driving

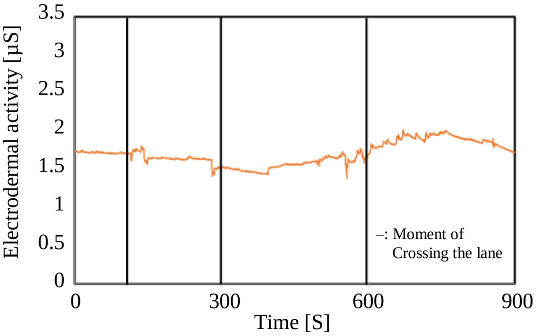

Fig. 5. Electrodermal activity of during Level 2 driving

In this graph, the vertical axis represents the electrodermal activity, and the horizontal axis represents time. In the Level 1 experiment, the electrodermal activity increased when the driver started driving. Subsequently, the electrodermal activity showed a continuous decrease over time and stabilized at approximately 0.5 μS. The subjects held the steering wheel at all times for 15 min during the experiment. The subjects continued to drive without deviating from their lane.

The black line in Fig. 5 represents the subject's driving takeover when the automated vehicle crosses the lane. The electrodermal activity did not decrease significantly with time in Level 2 driving compared with Level 1 driving. In addition, the electrodermal activity sometimes changed after the takeover. This indicates that the driver's sense of urgency is heightened by the situation of the automated vehicle. A bar graph of the results of the questionnaires administered in the six categories is presented in Fig. 6.

Physical Demand and Temporal Demand were higher at Level 1 than at Level 2. However, Frustration was higher at Level 2 than at Level 1. There were no significant differences between the two levels for other items.

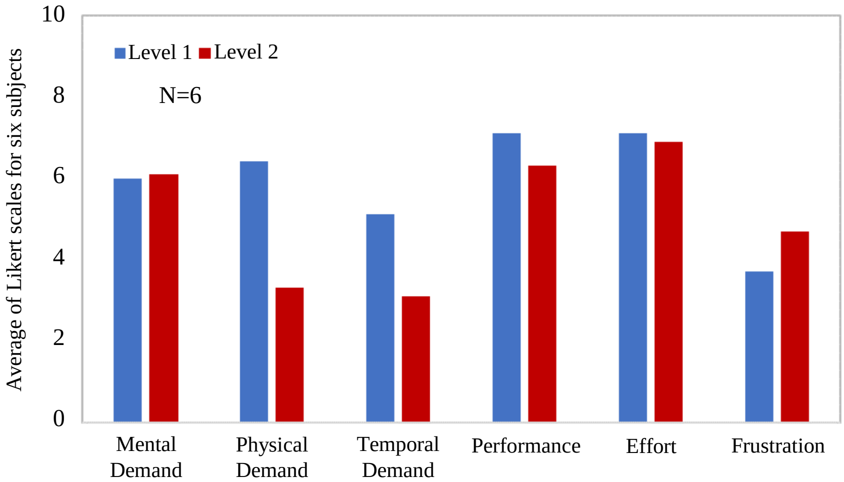

Fig. 6. Comparison of subjects' questionnaire results

6. Discussion

The questionnaire results confirmed that physical demand items were significantly lower for Level 2 than for Level 1. However, the results for the Mental Demand and Frustration items were the same or slightly higher for Level 2 than for Level 1. Because lane departure occurred during automatic driving, the subjects had to concentrate constantly on the driving situation. Therefore, the mental demand and the level of dissatisfaction increased. Drivers are likely to experience stress when there is the possibility of unpredictable movement of automated vehicles. Therefore, even if the physical demand is decreased by increasing the level of automated driving, the mental demand may not decrease depending on the interface and accuracy of the automated driving. In experiments using Level 2 automated vehicles, the electrodermal activity response occurred when the driver took over driving after the vehicle veered out of its lane. This condition may indicate that the driver was temporarily stressed. Some subjects also showed increased electrodermal activity after straying out of their lanes. In addition, the electrodermal activity decreased for some subjects in the Level 1 car experiment; this is attributed to the fact that they became more relaxed and accustomed to driving. Utilizing electrodermal activity (EDA) for a quantitative assessment of driving behavior, Fig. 5 displays the first instance of Skin Conductance Response (SCR) [22] following an intervention. Regarding the initial stimulus onset, the latency measured 4 seconds, rise time was 1 second, and half-recovery time was 1 second. At this moment, the amplitude registered 0.07μS. Furthermore, it required 15 seconds for the physiological response to return to a steady state. By analysing the electrodermal activity, it is possible to observe changes over time in the driver's mental load that the questionnaire did not reveal.

7. Conclusion

The measurement results for the subjects' mental fatigue using the proposed method showed that increasing the level of automatic operation did not necessarily decrease a driver's mental load. By observing points where SCR reactions with amplitudes ranging from 0.05 to 0.6μS occurred, it became feasible to analyze distinctive driving behavior through examining acceleration and driver actions. Specifically, responses to deviations from the intended line (caused by the operator) and unexpected actions without external intervention were discernible. A preponderance of participants exhibited diminished responses with repeated interventions compared to the first instance.Employing this system, a comprehensive evaluation of driver behavior - both qualitative and quantitative - is facilitated by the quantitative assessment through SCR responses. This validation confirms the system's applicability as a simulator and evaluation system for designing safer and more comfortable systems.This method is expected to be valuable in designing interfaces with reduced mental fatigue. Future experimental studies should be conducted with a broad range of ages and experiences of subjects, as well as under other automatic driving conditions.

References

[1] Liu Y, Cui W, Zhou R, Chan AHS. The effects of social conformity and gender on drivers' behavioural intention towards level-3 automated vehicles. Travel Behav Soc. 2022;29:330-338.

[2] Manawadu UE, Kamezaki M, Ishikawa M, Kawano T, Sugano S. A haptic feedback driver-vehicle interface for controlling lateral and longitudinal motions of autonomous vehicles. 2016 IEEE International Conference on Advanced Intelligent Mechatronics (AIM); 2016 Jul 12-15; Banff, Canada. USA: IEEE; 2016. p. 119-124

[3] Nakayama M, Miura S, Kawano S, Koreeda Y, Yamamoto A, Fukumoto R, et al. Estimation technique of the destined target with gesture recognition for the development of in-car interface of automated driving vehicle. Transactions of the JSME (in Japanese). 2015;81(832):1-17. (In Japanese)

[4] Large DR, Banks V, Burnett G, Margaritis N. Putting the joy in driving: investigating the use of a joystick as an alternative to traditional controls within future autonomous vehicles. The 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications; 2017 Sep 24-27; Oldenburg, Germany. New York: ACM; 2017. p. 31-39.

[5] Petersen L, Tilbury D, Yang XJ, Robert L. Effects of augmented situational awareness on driver trust in semiautonomous vehicle operation. 2017 NDIA Ground Vehicle Systems Engineering and Technology Symposium; 2017 Aug 8-10; Novi, United State. p. 1-7.

[6] Mok B, Johns M, Yang S, Ju W. Actions speak louder: Effects of a transforming steering wheel on posttransition driver performance. IEEE 20th International Conference on Intelligent Transportation Systems (ITSC); 2017 Oct 16-19; Yokohama, Japan. USA: IEEE; 2017. p. 1-8.

[7] Capallera M, Meteier Q, de Salis E, Angelini L, Carrino S, Khaled OA, et al. Owner manuals review and taxonomy of ADAS limitations in partially automated vehicles. 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications; 2019 Sep 21-25; Utrecht, Netherlands. New York: ACM; 2019. p. 156-164.
[8] Petersen L, Robert L, Yang XJ, Tilbury DM, et al. Situational awareness, drivers trust in automated driving systems and secondary task performance. arXiv preprint arXiv:1903.05251. 2019:1-26.
[9] Chen W; Sawaragi T, Horiguchi Y. Measurement of driver's mental workload in partial autonomous driving. IFAC-PapersOnLine. 2019;52(19):347-352.
[10] Walker F, Boelhouwer A, Alkim T, Verwey WB, Martens MH. Changes in Trust after Driving Level 2 Automated Cars. J Adv Transp. 2018;2018:1-9.
[11] Ruijten PAM, Terken JMB, Chandramouli SN. Enhancing trust in autonomous vehicles through intelligent user interfaces that mimic human behavior. Multimodal Technol Interact. 2018;2(4):62.
[12] Detjen H, Pfleging B, Schneegass S. A wizard of oz field study to understand non-driving-related activities, trust, and acceptance of automated vehicles. 12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications; 2020 Sep 21-22; Virtual Event, USA. New York: ACM; 2020. p. 19-29.
[13] Shahrdar S, Park C, Nojoumian M. Human trust measurement using an immersive virtual reality autonomous vehicle simulator. Proceedings of the 2019 AAAI/ACM Conference on AI, Ethics, and Society; 2019 Jan 27-28; Honolulu, USA. New York: ACM; 2019. p. 515-520.
[14] Schwarz C, Gaspar J, Brown T. The effect of reliability on drivers' trust and behavior in conditional automation. Cogn Tech Work. 2019;21:41-54.
[15] Němcová A, Svozilová V, Bucsuházy K, Smíšek R, Mézl M, Hesko B, et al. Multimodal features for detection of driver stress and fatigue. IEEE Trans Intell Transp Syst. 2020,22(6):3214-3233.
[16] Zontone P, Affanni A, Bernardini R, Piras A, Rinaldo R. Stress detection through electrodermal activity (EDA) and electrocardiogram (ECG) analysis in car drivers. 27th European Signal Processing Conference (EUSIPCO); 2019 Sep 2-6; A Coruna, Spain. USA: IEEE; 2019. p. 1-5.
[17] Morris DM, Erno JM, Pilcher JJ. Electrodermal response and automation trust during simulated self-driving car use. Proc Hum Factors Ergon Soc Annu Meet. 2017;61(1):1759-1762.
[18] Walker F, Wang J, Martens MH, Verwey WB. Gaze behaviour and electrodermal activity: objective measures of drivers' trust in automated vehicles. Transp Res Part F Traffic Psychol Behav. 2019;64:401-412.
[19] SAE International. Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles. USA: Society of Automotive Engineers; 2021.
[20] Mok B, Ju W. The push vs pull of information between autonomous cars and human drivers. 6th International Conference on Automotive User Interfaces and Interactive Vehicular Applications; 2014 Sep 17-19; Seattle, USA. New York: ACM; 2014. p. 1-5.
[21] Unity Asset store. Vehicle Physics Pro - Community Edition [Internet]. 2019 [cited 2023 Jan 20]. Available from: https://assetstore.unity.com/packages/tools/physics/vehiclephysics-pro-community-edition-153556?locale=ja-JP. (In Japanese).
[22] Fukuda H. How can physiological measurements contribute to Man-Environment research?. MERA J. 2018;41:67-75. (In Japanese)