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Design and Development of a Tactile Takeover Warning System Using a Tactile Seat for Automated Driving

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ABSTRACT

Designing an effective takeover warning system is crucial for driving safety in conditionally automated vehicles. Given the advantages of the tactile modality in presenting takeover requests (TORs), this study designed and developed a seat-based tactile takeover warning system. A directional tactile TOR was used to instruct drivers on how to respond in various takeover scenarios. Additionally, the urgency of the tactile TOR was dynamically mapped to the time to collision with the hazard ahead, helping drivers perceive their proximity to the hazard. To evaluate the effectiveness of this novel takeover warning system, we recruited 24 participants and conducted a simulated driving study under varying levels of takeover event urgency and weather conditions. The results indicated that the developed tactile takeover warning system significantly reduced drivers' takeover time, regardless of the urgency level or weather condition. Therefore, this system has strong potential to enhance takeover performance and merits adoption by relevant practitioners.

Keywords: Tactile seat, Automated driving, Takeover request, Driving behaviour

INTRODUCTION

With the advancement of cutting-edge technologies such as the Internet of Things and computer vision, automated driving has rapidly evolved over the past decade. It holds great potential to alleviate traffic congestion, enhance driving safety, and improve passenger experience (Hussain & Zeadally, 2019). SAE International (2021) classifies automated driving into six levels (L0–L5). Currently, partially automated driving (L2) has been widely commercialized, with Tesla being a notable example. Conditionally automated driving (L3) is expected to enter the consumer market in the near future. L3 automation allows drivers to engage in various non-driving-related tasks (NDRTs) while the system is active. However, when the automated driving system exceeds its operational design domain (ODD), drivers must promptly resume control of the vehicle. Therefore, delivering an effective takeover request (TOR) is crucial to ensuring driving safety.

Utilizing the tactile modality to convey TORs offers several advantages. First, previous studies have shown that visual and auditory TORs can be disrupted by various visual and auditory NDRTs (Chai et al., 2024; Petermeijer et al., 2016). In contrast, tactile TORs are not susceptible to such interference. Second, the takeover process primarily involves visual-manual tasks. According to multiple resource theory (MRT), cognitive resources allocated to different modalities function independently and do not interfere with one another (Wickens, 2002). This allows drivers to simultaneously monitor the surrounding traffic environment (a visual task) while perceiving tactile TORs, thereby facilitating a more efficient takeover process (Meng & Spence, 2015; Petermeijer et al., 2017). These findings highlight the significant potential of employing tactile TORs in automated vehicles to enhance both safety and efficiency.

Thus, this study designed and developed a seat-based tactile takeover warning system aimed at enhancing drivers' takeover performance. Additionally, we conducted a simulated driving experiment to assess the effectiveness of the tactile warning system.

DESIGN AND DEVELOPMENT OF THE TACTILE TAKEOVER WARNING SYSTEM

We integrated 10 vibrotactile motors into a seat, with six positioned on the seat pan and four on the seat back, arranged symmetrically relative to the seat center (as shown in Figure 1). Using this setup, we developed a novel tactile takeover warning system. The system primarily encoded information through vibration location and timing to assist drivers in taking over control.

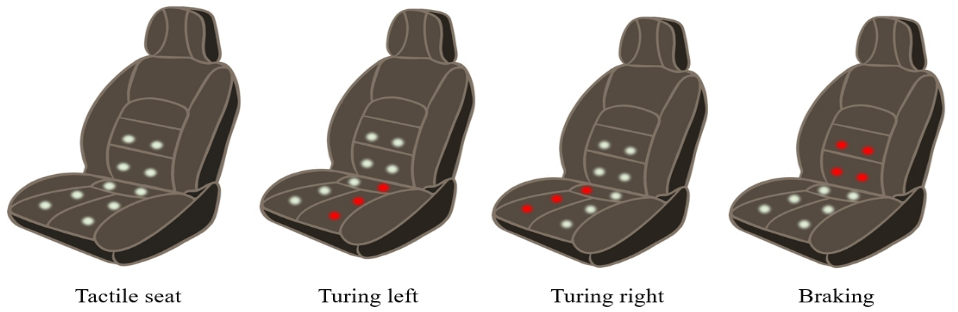

Figure 1: Tactile seat and vibration pattern. Cyan circles represent vibration motors, while red circles denote activated vibration motors.

For the vibration location dimension, when drivers needed to steer left, right, or brake, the system activated the three motors on the corresponding side of the seat pan or the four motors on the seat back to indicate the required action.

For the vibration timing dimension, TOR urgency was manipulated by adjusting inter-pulse intervals, dynamically mapping urgency to the criticality of the situation as the vehicle approached a hazard (a looming TOR). Previous research has shown that a looming TOR enhances drivers' awareness of the temporal proximity to a hazard and improves takeover performance (Shi et al., 2024). The duration of each tactile pulse was set to 200 ms, and the inter-pulse intervals were dynamically controlled in real-time based on the time-to-collision (TTC) with the front hazard. The relationship between inter-pulse intervals (modulating perceived urgency) and TTC was modeled as follows, based on the study by Shi et al. (2024):

$$Pulse\ interval = 38.07 * TTC + 1.41 \quad (1)$$

Through these design elements, our tactile takeover warning system aimed to enhance drivers' takeover performance effectively.

SYSTEM EVALUATION

Participants

A total of 24 participants were recruited for the experiment, all of whom held a valid Chinese driving license. The participants had an average age of 25.75 years and an average driving experience of 5.79 years.

Simulator

The evaluation experiment was conducted using a three-screen driving simulator (as shown in Figure 2). The simulated driving system comprised driving software (STISIMDRIVE-M1000-R), a control system (Logitech G29, including a steering wheel, brake, and accelerator), an adjustable seat, a high-performance workstation (Nvidia GeForce RTX 3080 [10GB], Intel Core i7-10700K), speakers, and three 32-inch displays (1366 × 768 pixel resolution), providing a 135° field of view.

Figure 2: The driving simulator.

Experimental Procedures

Upon arrival, participants signed a consent form and completed a demographic questionnaire. The experimenter introduced them to the nature of L3 automated driving, the purpose of the experiment, and the meanings of various tactile TORs. Participants then completed a practice session to familiarize themselves with automated driving and the takeover process.

During the formal experiment, participants completed two driving blocks. One block corresponded to our developed novel takeover warning system, while the other served as a baseline, featuring a standard tactile TOR consisting of three 200 ms tactile pulses with a fixed interval of 240 ms, activating all motors on the seat. Each block contained six driving trials, varying in takeover urgency (urgent [TTC = 4 s] vs. non-urgent [TTC = 8 s]) and weather conditions (sunny, light fog [visibility = 200 m], and heavy fog [visibility = 50 m]). The sequence of the six trials was randomly arranged.

During automated driving, participants were required to engage in a Tetris game as a NDRT. Additionally, there were two types of takeover events: braking and lane-changing maneuvers, with event types randomly assigned across trials. Between each trial, participants took a short break and completed subjective rating scales. The entire experiment lasted approximately 45 minutes.

RESULTS

We used a linear mixed model to analyze the data. It was found that regardless of takeover event urgency and weather conditions, our developed novel takeover warning system significantly reduced takeover time ($ps < .05$) (as shown in Table 1).

Table 1: Means and standard deviations of takeover time (s) under various conditions.

	Baseline	Novel Takeover Warning System
Weather condition		
Heavy Fog (visibility = 50 m)	2.67 ± 1.18	1.85 ± 0.45
Light Fog (visibility = 200 m)	2.42 ± 1.05	1.89 ± 0.66
Sunny	2.68 ± 1.07	1.94 ± 0.50
Event urgency		
Urgent (TTC = 4 s)	2.05 ± 0.43	1.75 ± 0.33
Non-Urgent (TTC = 8 s)	3.12 ± 1.29	2.04 ± 0.66

DISCUSSION

Given the advantages of the tactile modality in presenting TORs, this study developed a tactile seat and designed a novel takeover warning system based on vibration location and timing dimensions. Directional tactile information provided drivers with clear guidance on how to respond to takeover events (Cohen-Lazry et al., 2019; Shi et al., 2022), while looming information helped them better perceive the urgency of the situation and their proximity to the hazard (Shi et al., 2024).

Our evaluation experiment demonstrated that the novel tactile takeover warning system effectively reduced takeover time, regardless of event urgency and weather conditions. These findings highlight the robustness of the developed system in improving drivers' takeover performance, offering practical implications for automotive industry practitioners.

However, in real-world driving environments, vehicle vibrations caused by motor operation and uneven road surfaces may create masking effects, potentially interfering with drivers' perception of tactile takeover cues (Wan & Wu, 2018). Therefore, further research is needed to assess the effectiveness of the developed tactile takeover system in real-world conditions and explore design enhancements to mitigate the negative impact of vehicle vibrations.

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