Project 2164 | September 2022

SJSU SAN JOSÉ STATE UNIVERSITY

MTI MINETA TRANSPORTATION INSTITUTE

Exploring the Effects of Meaningful Tactile Display on Perception and Preference in Automated Vehicles

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Mineta Transportation Institute

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Report 22-42

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September 2022

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A publication of the
Mineta Transportation Institute
Created by Congress in 1991

College of Business
San José State University
San José CA 95192-0219

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. 22-42	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Exploring the Effects of Meaningful Tactile Display on Perception and Preference in Automated Vehicles		5. Report Date September 2022 6. Performing Organization Code
7. Authors Kimberly D. Martinez: 0000-0002-8487-8368 Gaojian Huang, Ph.D.: 0000-0001-8139-7481		8. Performing Organization Report CA-MTI-2164
9. Performing Organization Name and Address		10. Work Unit No. 11. Contract or Grant No. 69A3551747127
12. Sponsoring Agency Name and Address U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology University Transportation Centers Program 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Covered 14. Sponsoring Agency Code
15. Supplemental Notes		

16. Abstract

There is an existing issue in human-machine interaction, such that drivers of semi-autonomous vehicles are still required to take over control of the vehicle during system limitations. A possible solution may lie in tactile displays, which can present status, direction, and position information while avoiding sensory (e.g., visual and auditory) channels overload to reliably help drivers make timely decisions and execute actions to successfully take over. However, limited work has investigated the effects of meaningful tactile signals on takeover performance. This study synthesizes literature investigating the effects of tactile displays on takeover performance in automated vehicles and conducts a human-subject study to design and test the effects of six meaningful tactile signal types and two pattern durations on drivers' perception and performance during automated driving. The research team performed a literature review of 18 articles that conducted human-subjects experiments on takeover performance utilizing tactile displays as takeover requests. Takeover performance in these studies were highlighted, such as response times, workload, and accuracy. The team then conducted a human-subject experiment, which included 16 participants that used a driving simulator to present 30 meaningful vibrotactile signals, randomly across four driving sessions measuring for reaction times (RTs), interpretation accuracy, and subjective ratings. Results from the literature suggest that tactile displays can present meaningful vibrotactile patterns via various in-vehicle locations to help improve drivers' performance during the takeover and can be used to assist in the design of human-machine interfaces (HMI) for automated vehicles. The experiment yielded results illustrating higher urgency patterns were associated with shorter RTs and higher intuitive ratings. Also, pedestrian status and headway reduction signals presented shorter RTs and increased confidence ratings compared to other tactile signal types. Finally, the signal types that yielded the highest accuracy were the surrounding vehicle and navigation signal types. Implications of these findings may lie in informing the design of next-generation in-vehicle HMIs and future human factors studies on human-automation interactions.

17. Key Words Human factors, Driver vehicle interfaces, Intelligent vehicles, Tactile perception, Autonomous vehicle handover	18. Distribution Statement No restrictions. This document is available to the public through The National Technical Information Service, Springfield, VA 22161.		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 23	22. Price

Form DOT F 1700.7 (8-72)

DOI: 10.31979/mti.2022.2164

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Acknowledgments

This work was supported by the U.S. Department of Transportation and Mineta Transportation Institute (grant #: 69A3551747127). We would also like to thank undergraduate student Brenna Nettles-Miller for assisting with data collection, and Collin Li for interface development.

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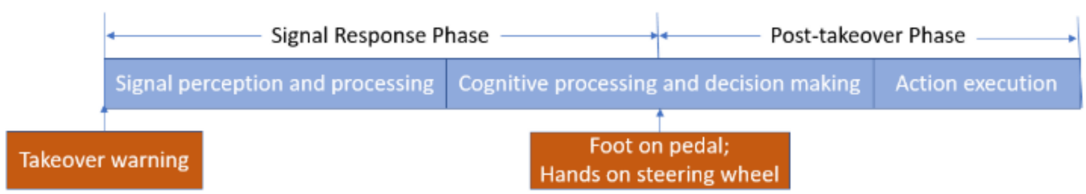
1. Introduction

Vehicles on the roadway are becoming semi- or fully autonomous (Society of Automotive Engineers (SAE), 2021). Although these vehicles can drive automatically, hazardous conditions could expose the vehicle's system limitations (e.g., in SAE Levels 2-3) and may prompt the vehicle to suddenly request the driver to take over (McDonald et al. 2019). The takeover process is a two-phase model (see Fig. 1) that consists of the signal response and post-takeover phases (Huang and Pitts 2022). The signal response process begins with the driver perceiving and processing the takeover request and quickly becoming aware of their surroundings, then moving their hands and feet to the driving position to prepare to resume manual control of the vehicle. The driver then enters the post-takeover phase, where they need to assess the driving environment while quickly creating and executing vehicle maneuvering decisions—all in a short period of time (Petermeijer, de Winter, and Bengler 2016; Huang and Pitts 2022).

Figure 1. The Takeover Model



Source: Huang & Pitts, 2022; Petermeijer et al., 2016

This takeover process may be further exacerbated when information on the driving environment is overwhelming, which could overload the driver's sensory channels. For example, a takeover in an urban area may require the driver to both perceive and process information about the status (the object's speed and acceleration, or whether it is moving or stationary) and location of all surrounding/oncoming vehicles, pedestrians, cyclists, and traffic signs/signals, all of which may overstimulate the driver's visual resources. In addition, auditory resources may be suppressed by surrounding noises, such as non-driving-related-tasks (NDRTs) or the sounds of traffic. In this case, quickly conveying information to drivers while avoiding an increase to their cognitive workload is imperative for the safety of semi-autonomous driving. Based on the Multiple Resource Theory (Wickens 2008), sensory modalities are relatively independent, and overloaded information in one channel (e.g., visual) may not impact the information presented in other channels (e.g., tactile). Thus, an effective human-machine interface (HMI) that utilizes idle sensory modalities is crucial. Tactile displays may therefore be a more reliable option than visual or auditory displays to convey real-time information that can quickly attract drivers' attention and help guide their driving throughout the entire takeover process in complex driving environments.

Research has shown that tactile displays, placed in various in-vehicle locations (e.g., seatback, pan, belt, hands, wrists, and steering wheel), can be used as takeover requests by producing vibrotactile patterns to convey more meaningful and complex information, such as the location, urgency, and direction of in-motion objects in the surrounding environment during takeover (Telpaz et al. 2015; Fitch et al. 2011; Ege, Cetin, and Basdogan 2011; Pielot, Krull, and Boll 2010). This information was either presented in instructional (i.e., representing vehicle maneuvering commands) or informative (i.e., indicating elements in the driving environment, such as pedestrians and vehicles) formats and has shown positive effects in helping drivers yield better takeover performance (Huang 2021; Erp and Veen 2001a; Morrell and Wasilewski 2010; Telpaz et al. 2015). For example, an experiment conducted by Erp and Veen (2001) illustrated that compared to visual, tactile, and visuotactile (i.e., the combination of visual and tactile) displays, a tactile display embedded into the driver's seat to instruct drivers of navigational signals (e.g., proceed left/right or continue straight) resulted in shorter reaction times. In addition, an experiment conducted by Huang et al. (2019) compared the effects of uni-, bi-, and tri-modal combinations of visual (V), auditory (A), and tactile (T) cues on response time to takeover alerts in a driving simulator. The study utilized a belt with two tactors located on the lower back to warn drivers of the need for takeover and found that signals with a tactile component (T, VT, AT, VAT) resulted in the shortest response times to takeover requests, compared to signal types that did not include tactile signals (V, A, VA). Because this type of display can represent meaningful and complex information, such as status, direction and position, and are more available compared to visual and auditory channels in the driving environments, it is important to understand the effects of meaningful tactile patterns, as takeover requests, on takeover performance. However, to date, limited work has explored the effectiveness of these meaningfully complex tactile signals. Therefore, the goal of this study was to first, synthesize the literature concerning the effects of tactile displays on takeover performance in automated vehicles, and second, based on the synthesis, design and test the effects of six signal types (navigation, speed, location/status of surrounding vehicles, over the speed limit, headway reductions, and pedestrian status) and two pattern durations (lower and higher urgencies), on drivers' perceptions and performance during automated driving.

2. Methods

2.1 Literature Review

A literature search was performed in September 2021. Keywords included “automated/autonomous driving,” “haptics,” and “tactile,” while limiting the search to articles that involved controlled experiments between the years 2000–2022. The primary focus was on human factors and ergonomics journals and proceeding publications, such as *Human Factors*, *Accident Analysis & Prevention*, *Applied Ergonomics*, *Transportation Research Part F: Traffic Psychology and Behavior*, and the *IEEE International Conference on Human-Machine Systems*, etc. Articles that conducted human-subject experiments on automated vehicle takeover performance and used tactile displays as takeover requests were included. This resulted in a total of 18 relevant articles.

Based on the information presented by tactile displays, these articles were categorized into two groups: informative and instructional signal groups. Each group had a total of nine articles. The informative signal group are studies that convey information in the driving environment, such as the location of vehicles and pedestrians in the surrounding area. The instructional signal group are studies that used tactile displays as commands for appropriate driving maneuvers i.e., instructions for drivers to change their own vehicle’s status/location, such as to slow down or change lanes. Driving metrics reported across studies, as indicators of takeover performance, are highlighted, such as response time, workload, and information interpretation accuracy.

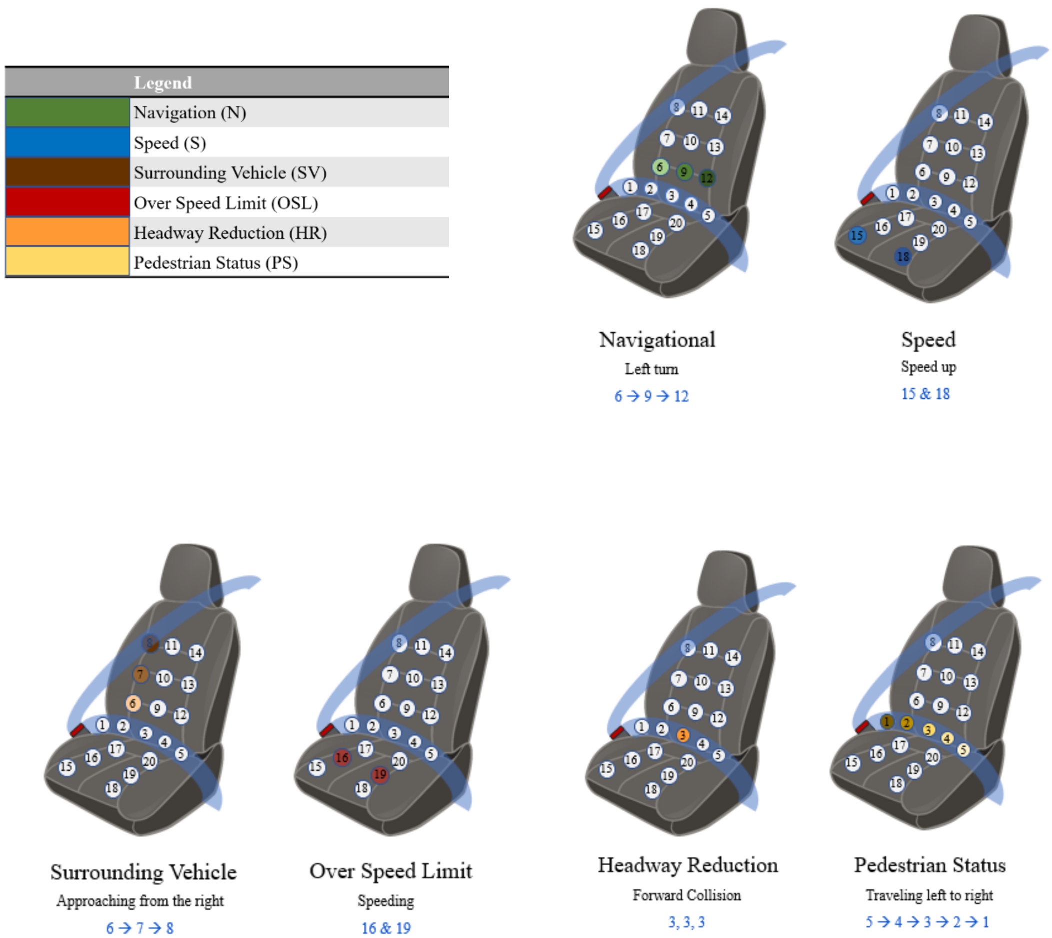
2.2 Human-subject Experiment

For the human-subject experiment, 16 college students were recruited; inclusion criteria included having a valid driver’s license, normal or corrected-to-normal vision, and no cognitive/neurological impairments to the sense of touch. Two hours of class credits were given to all participants as compensation for their time. The study was approved by the San Jose State University’s Institutional Review Board (IRB Protocol ID: 21208). The experiment was conducted using a medium-fidelity driving simulator that was self-assembled; system accessories included a 65-inch Sony TV monitor, a Logitech G27 steering wheel/foot pedals, a Cobra Monaco E36 life-size bucket seat, and a simulated makeshift seat belt (see Fig. 2).

Figure 2. Experimental Setup and Apparatus

Twenty piezo-buzzers (or C-2 tactors; shown as the numbered circles on the seat and seat belt in Fig. 3) sent tactile signals. In total, six signal types (Table 1) were presented: navigational (left turn, right turn, U-turn), speed (speed up/slow down), surrounding vehicle location (left, behind, right) and status, over the speed limit, headway reductions (forward collision), and pedestrian status (traveling left-to-right or right-to-left). Fig. 3 shows example patterns.

Figure 3. Example Pattern Descriptions for All Six Warning Signal Types



The study had six signal types: navigation, speed, surrounding vehicle, over the speed limit, headway reduction, and pedestrian status. It also had two patterns for each of these signals: lower urgency and higher urgency. The study employed a 6×2 (signal type by pattern) full factorial design, allowing for the estimation of main effects and interactions, where signal type and patterns were within-subject factors. These six tactile signal types were presented in three locations, the seat back, pan, and belt, and represented the most common takeover scenarios from the literature. Lower urgency patterns were represented by longer signal bursts and interstimulus interval (ISI) durations. Higher urgency patterns were represented by shorter signals, bursts, and ISI durations with a repetition of the signal. A summary of the examined signals can be found in Table 1.

Table 1. A Summary of Tactile Signals and Patterns Used in the Study

TACTOR SEQUENCE	DISPLAY LOCATION	WARNING SIGNAL	PATTERN: LOW URGENCY	PATTERN: HIGH URGENCY
INSTRUCTIONAL (5)				
NAVIGATIONAL WARNING SIGNAL (3)				
2 > 3 > 4	BELT	LEFT TURN	(3X 215MS ON)	(3X 107.5MS ON)
6 > 9 > 12	BACK	LEFT TURN	(3X 215MS ON)	(3X 107.5MS ON)
4 > 3 > 2	BELT	RIGHT TURN	(3X 215MS ON)	(3X 107.5MS ON)
12 > 9 > 6	BACK	RIGHT TURN	(3X 215MS ON)	(3X 107.5MS ON)
3 > 4 > 12	BELT	U-TURN	(3X 215MS ON)	(3X 107.5MS ON)
15 > 18 > 19	PAN	U-TURN	(3X 215MS ON)	(3X 107.5MS ON)
SPEED WARNING SIGNALS (2)				
2 & 4	BELT	SPEED UP	(3X 215MS ON, 215MS OFF)	(3X 107.5MS ON, 107.5MS OFF)
15 &18	PAN	SPEED UP	(3X 215MS ON, 215MS OFF)	(3X 107.5MS ON, 107.5MS OFF)
6 & 12	BACK	SLOW DOWN	(3X 215MS ON, 215MS OFF)	(3X 107.5MS ON, 107.5MS OFF)
17 & 20	PAN	SLOW DOWN	(3X 215MS ON, 215MS OFF)	(3X 107.5MS ON, 107.5MS OFF)
INFORMATIVE (5)				
SURROUNDING VEHICLES WARNING SIGNAL (2)				
12 > 13 > 14	BACK (LEFT)	BACK LEFT	(3X 215MS ON)	(3X 107.5MS ON)
9 > 10 > 11	BACK (CENTER)	BACK	(3X 215MS ON)	(3X 107.5MS ON)
6 > 7 > 8	BACK (RIGHT)	BACK RIGHT	(3X 215MS ON)	(3X 107.5MS ON)
20 > 19 > 18	PAN (LEFT)	PAN, LEFT SIDE, BACK-TO-FRONT	(3X 215MS ON)	(3X 107.5MS ON)
17 > 16 > 15	PAN (RIGHT)	PAN, RIGHT SIDE, BACK-TO-FRONT	(3X 215MS ON)	(3X 107.5MS ON)
OVER SPEED LIMIT WARNING SIGNAL (1)				
7 & 13	BACK	SPEEDING	(3X 215MS ON, 215MS OFF)	(3X 107.5MS ON, 107.5MS OFF)
16 & 19	PAN	SPEEDING	(3X 215MS ON, 215MS OFF)	(3X 107.5MS ON, 107.5MS OFF)

Tactor Sequence	Display Location	Warning Signal	Pattern: low urgency	Pattern: high urgency
Headway Reduction (1)				
3, 3, 3	Belt	Forward Collision	(215ms on, 4800ms off, 215ms on, 3440ms off, 215ms on, 1200ms off) + 1800ms off delay	(107.5ms on, 2400ms off, 107.5ms on, 1720ms off, 107.5ms on, 600ms off) + 1800ms off delay
Pedestrian Status Warning Signal (1)				
1>2>3>4>5	Belt	Pedestrian traveling right to Left	(5x 215ms on, 2500ms off)	(5x 107.5ms on, 1250ms off)
5>4>3>2>1	Belt	Pedestrian traveling left to Right	(5x 215ms on, 2500ms off)	(5x 107.5ms on, 1250ms off)

A total of 120 tactile signals were randomly presented; 20 signals presented three times each in two patterns, in a driving task separated by four driving sessions that were designed to represent SAE Level 3 automated driving. Three dependent variables were measured: participants' reaction times to the signals, their interpretation accuracy, and subjective ratings on the signals. Prior to beginning the experiment, participants were given an overview of the study, a consent form, and a pre-experiment questionnaire. Then, participants were introduced to a brief training session to learn the driving setup, experiment procedures, and to study the vehicle "manual" listing all of the driving scenarios and their associated vibrotactile signals/patterns. Beginning the experiment, participants were informed that the vehicle was an SAE Level 3 automated vehicle that did not require constant manual control. Tactile patterns would play on the driver's seat (back or pan) and seat belt at random. Participants were asked to execute a response (e.g., pressing a button), only after they had an answer for the actual meaning that the tactile signal represented, as quickly as they would in real-life takeover. Once the button was pressed, participants had to state their interpretation of the signal and, on a scale of 1 (low) to 5 (high), rate their confidence in their answer and the intuitiveness of the tactile signals. At the end of the experiment, which lasted approximately two hours, participants filled out a post-experiment questionnaire and were debriefed. A two-way repeated measure analysis of variance (ANOVA) was conducted to analyze the data, with tactile signal and pattern as independent variables.

3. Results

3.1 Findings from the Literature Review

Collectively, results across informative studies demonstrated that dynamic vibrotactile patterns reliably represent spatial distance information for obstacles in the driving environment, which was shown to improve driving performance by reducing reaction times (RTs), increasing situation awareness and causing drivers to have a more systematic scan of the driving environment. Very few studies were found to investigate the use of a tactile display to represent the status and location of pedestrians in the driving environment, which is imperative for pedestrian safety during a takeover in urban areas. Similarly, results across instructional studies found that navigation research has demonstrated that tactile displays intuitively present external directional information by utilizing the body as a mapping system, linking perceived stimuli to external directions. These studies used tactile displays embedded in various locations, such as the seat back, pan, belt, or steering wheel, to represent vibrotactile navigation signals and have shown quicker RTs, decreased workload, and an increase in directional information interpretation accuracy. However, current studies have not examined signals that contain other instructional information, such as U-turn patterns or navigational cues (e.g., Borojeni et al. 2017; Ege, Cetin, and Basdogan 2011; van Erp 2001). Future studies may need to explore how meaningful tactile patterns represent different takeover scenarios (in different patterns, urgency levels, and locations) and may affect drivers' information processing and decision making, as well as task performance. Our human-subject experiment takes a step in investigating how people interpret meaningful tactile patterns during takeover.

3.2 Findings from the Human-subject Experiment

Meaningful tactile signal types and patterns were investigated for the effects of three dependent variables: reaction time, accuracy, and subjective satisfaction during a semi-autonomous drive. The study found that, compared to other tactile signal types, pedestrian status signals and headway reduction signals resulted in shorter reaction times and higher confidence ratings. Moreover, of all the signal types, higher accuracy of information interpretation was found for surrounding vehicle and navigation signal types. Lastly, when signals were presented as higher urgency patterns, shorter RTs and higher intuitive ratings than they were for lower urgency patterns resulted.

4. Summary and Conclusion

In summary, the literature review illustrated that informative and instructional tactile signals were associated with better takeover performance, compared to driving with visual or auditory displays or without tactile displays (e.g., Chang, Hwang, and Ji 2011; Huang and Pitts 2022; Scott and Gray 2008; van Erp and van Veen 2004). Having human-machine interfaces that utilized idle sensory modalities was crucial in alerting drivers of the need to take over. Tactile displays were a reliable option in conveying real-time information that quickly attracted the driver's attention and helped guide their driving throughout the entire takeover process, as the tactile modality was more available compared to visual and auditory modalities in complex driving environments.

However, the takeover scenarios in these studies were relatively simple, often presenting only one type of signal, either informative or instructional, but not both. It is still unclear whether meaningful tactile signals, presenting multiple pieces of information in both informative and instructional formats at the same time, can still improve drivers' takeover performance. For example, in a complex environment (e.g., an urban area), when tactile displays present the location and status of pedestrians and surrounding vehicles (e.g., informative), as well as command drivers to change lanes or speed (i.e., instructional), takeover performance may be impaired if the driver experiences information overwhelming. Future research may need to quantify the effects of conveying both signal information types concurrently in complex environments on task performance.

Furthermore, these studies often only presented a tactile display in one in-vehicle location. Given that tactile displays can be placed in a wide range of locations (e.g., seat back, seat pan, seat belt, wrists, etc.) and can utilize a variety of patterns to convey more meaningful feedback information, future research may investigate how different placements of tactile displays can affect the driver's perception of meaningful tactile patterns during the takeover process. Although these studies widely varied in the methods, tasks, and conditions used, they provided evidence that tactile displays may be associated with better takeover performance. Results across studies illustrated that tactile displays lowered response times, increased situation awareness, and improved the accuracy of information interpretation during automated vehicle takeover compared to drivers without tactile displays. The literature review's findings helped the design of the follow-up human-subject experiment regarding the in-vehicle tactile display pattern and location design.

The experimental study measured the effects of meaningful tactile signals and patterns on reaction time, accuracy of information interpretation, and subjective satisfaction during semi-autonomous driving. In summary, shorter reaction times and higher intuitive ratings resulted from the presentation of higher urgency patterns, compared to lower urgency patterns. Of all the other warning signals, shorter reaction times and higher confidence ratings were found in pedestrians' status warnings and headway reduction signals. Similarly, the presentation of surrounding vehicle and navigation signal types were correlated with a higher accuracy of information interpretation compared to the other signal types.

There are some limitations of the study. First, our goal was to compare the tactile signals and patterns; thus, we did not collect data comparing displays that utilized different senses, such as visual and auditory. Future studies may directly compare competing interface technologies. In addition, our participants were between the ages of 18–27 and only represented college students. Since age, demographics, and driving experience can be a large influential factor in determining the effectiveness and usability of a product, future studies may include middle-aged and older drivers, with varying driving experience and demographics. Lastly, the study lasted approximately two-hours; since learning a new human-machine interface in two hours can be challenging, future studies may employ a better strategy for the time allocation.

These findings may inform the design of next-generation in-vehicle human-machine interfaces while providing broad impacts and intellectual merits to society and science. For example, a possible impact may be providing an HMI tool in assisting cognitively impaired drivers, including but not limited to deaf, autistic, and older drivers, such as perceptual, cognitive, and physical declines by helping them make decisions faster and more reliably. In addition, preliminary data for this study will be used to investigate the effects of meaningful tactile displays on automated vehicle takeover performance where actual takeovers will be performed and measured in complex situations, such as urban areas, ultimately contributing to future studies investigating the effects of tactile displays on next-generation human-machine interaction. Lastly, the findings provided engineers, scientists, and designers with empirical evidence needed to design future HMIs and automated systems.

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Dr. Huang joined San Jose State University as an Assistant Professor in the Department of Industrial and Systems Engineering in Fall 2021. Currently, he is the Director of the Behavior, Accessibility, and Technology Lab. He is also a Research Associate in the Mineta Transportation Institute and a Faculty Affiliate in the Center on Healthy Aging in Multicultural Populations at San Jose State University. He received Master's degrees in Cognitive Psychology from Purdue University and in Safety Management from Indiana University Bloomington in 2020 and 2016, respectively, and obtained his Ph.D. in Industrial Engineering from Purdue University in 2021.

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