

From Manual Driving to Automated Driving: A Review of 10 Years of AutoUI

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ABSTRACT

Abstract: This paper gives an overview of the ten-year development of the papers presented at the International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutoUI) from 2009 to 2018. We categorize the topics into two main groups, namely, manual driving-related research and automated driving-related research. Within manual driving, we mainly focus on studies on user interfaces (UIs), driver states, augmented reality and head-up displays, and methodology; Within automated driving, we discuss topics, such as takeover, acceptance and trust, interacting with road users, UIs, and methodology. We also discuss the main challenges and future directions for AutoUI and offer a roadmap for the research in this area.

Author Keywords

automated driving, autoui review, manual driving.

CCS Concepts

• General and reference~Surveys and overviews

INTRODUCTION

The automotive user interface (UI) is the design space where the driver, passengers, and other road users and the vehicle interact. Within this space, the designer aims to maximize safety, usability, usefulness, and pleasure for the users. With the development of vehicles over the last 100 years, different types of systems have been brought into the vehicles to satisfy the driver's and the passengers' needs, such as infotainment, driver assistance, navigation, and comfort systems.

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AutomotiveUI '19, September 21–25, 2019, Utrecht, Netherlands

© 2019 Association for Computing Machinery.
ACM ISBN 978-1-4503-6884-1/19/09...\$15.00
<https://doi.org/10.1145/3342197.3344529>

The vehicle is not merely considered as a transportation tool geographically, but rather as an increasingly more mobile device with communication and information exchange virtually everywhere. This phenomenon has been substantially accelerated with the development of new technologies that enable automated driving recently. Nevertheless, it inevitably creates many challenges for the research and development of automotive UIs.

From the perspective of the design space between the driver and the vehicle, Kern and Schmidt [65] investigated the number of input and output devices, their modality and placement by examining over 100 vehicles in the first International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutoUI) in 2009. Many more researchers talked about different interaction techniques, methods, and tools to reduce driver distraction as well as empirical studies to understand the interaction process between a driver/passenger with a vehicle or brought in devices. Since 2009, the AutoUI conference series has been striving to fill the gap in academic conferences around automotive interfaces and has become the premier forum for the UI research for the automotive community. It celebrated its tenth anniversary in 2018 and is expected to bring over 200 researchers and practitioners in the domain to exchange information related to research and education for automotive UI design and development in 2019. Although there are broader surveys of related research [73, 98], these conferences are not only the venue for presenting AutoUI research, but also provide an interesting history of the evolution of AutoUI research and challenges and help identify areas for future research.

In the remainder of the paper, we first describe the review method in Section 2 and then in Section 3, we present the main research topics identified over ten years of conference proceedings of AutoUI papers by conducting a comprehensive review. Then, in Section 4, we focus on the major topics

identified in manual driving and automated driving, discussing research developments. Furthermore, we discuss the main challenges explored in the ten years of conferences and current and future research directions in Section 5. Finally, we come to conclude in Section 6.

METHOD

We reviewed the main proceeding papers in the ten years the conferences from AutoUI'09 to AutoUI'18. The total number of papers in the main proceedings is 276, excluding poster papers from AutoUI'09 to AutoUI'15 and work-in-progress papers in adjunct proceedings from AutoUI'16 to AutoUI'18. We focused on these papers since they offer an intriguing overview of the research trends in AutoUI over the last decade from manual driving to automated driving. Three major research questions guided the analysis of the collected research, including (1) which topics have been investigated in AutoUI? (2) what are the major developments and key challenges in these topics? and (3) what are the potential future trends for AutoUI research? We then identified the major research topics involved in manual driving and automated driving, described their major development, and speculated the potential challenges and future directions during the transition from manual driving to automated driving.

REVIEW RESULTS OF AUTOUI PROCEEDINGS

Firstly, we present the trend of the number of the papers submitted and the acceptance rate over the last decade in Table 1. It shows that the number of submitted papers has been increasing over the years. The number of papers in the main proceedings was fairly stable before 2014 (between 22 and 25) and increased to 35 in 2018. The acceptance rate here was calculated as the number of papers in the main proceedings divided by the total number of papers submitted. It was gradually decreasing from 2009 to 2014 and has been gradually stabilized around 40% since 2015 and the average acceptance rate was 40%. We also found that among all the 276 papers, 143 (52.3%) papers (number of participants = 27.9 ± 17.3) were simulator-based studies while 45 (16.3%) papers (number of participants = 38.0 ± 50.7) were naturalistic driving studies. In the rest of the papers, 76 (27.5%) (number of participants = 53.4 ± 121.5) employed questionnaires, surveys, and focused groups, and 12 (4.3%) were review papers.

We also measured their influence by calculating the Total Google Citation numbers (#TGC) by February 1, 2019 and Normalized Google Citation numbers (#NGC), which were computed by #TGC divided by the number of years since their publication in Figure 1. Despite the fact that such measures might be not absolutely accurate, they indicate the relative importance of the papers to some extent [164]. It seemed that #TGC was decreasing over the years due to the duration since publication whereas #NGC tended to increase by 2015. Those published in 2018 had a small #NGC because it was not long before publication.

Over the last ten years, the AutoUI research topics have focused mainly on manual driving and recently on automated driving. As illustrated in Figure 2, the total number of papers

Year	09	10	11	12	13	14	15	16	17	18	Total
#Paper Submitted	40	52	51	67	67	79	80	85	85	94	700
#Paper Accepted	22	25	25	23	24	23	28	37	34	35	276
Acceptance Rate	55%	48%	49%	35%	35%	29%	35%	43%	40%	37%	40%

Table 1. The numbers of papers submitted and reviewed and the acceptance rate over the years.

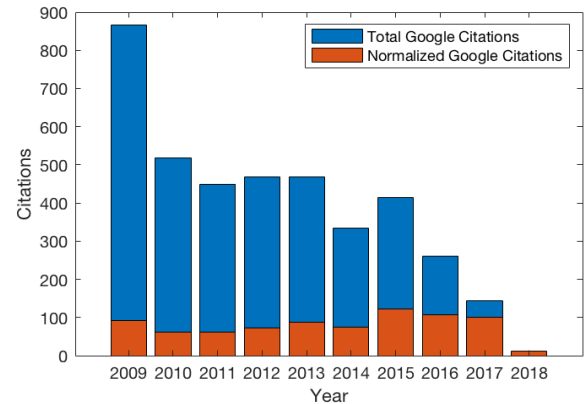


Figure 1. Total & normalized Google citations over the years.

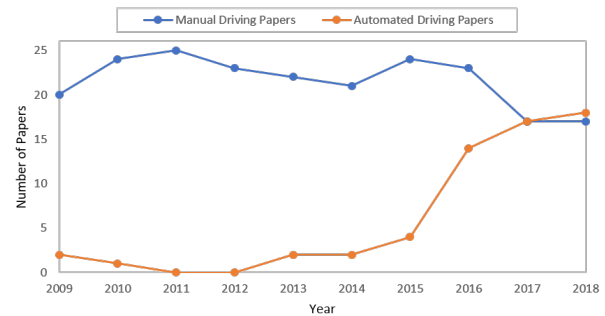


Figure 2. The numbers of manual and automated driving papers over the last 10 years.

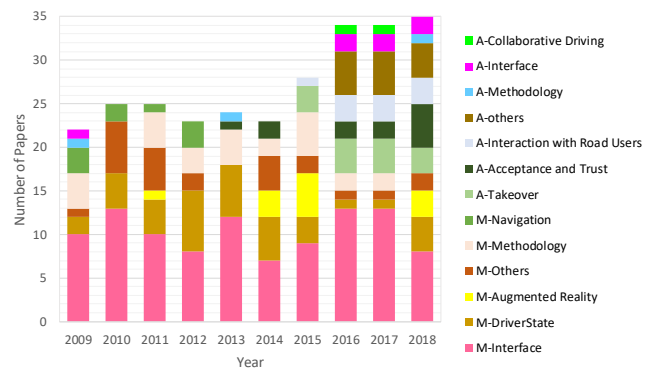


Figure 3. Research areas in the AutoUI over the last 10 years.

related to automated driving was 60 (i.e., 21.7%) which was less than the number of papers related to manual driving (216, i.e., 78.3%). The average of automated driving related papers was 1 paper/year up to 2014. However, since 2014, the research interests in automated driving have been growing steadily, evidenced by the increasing number of papers related to automated driving in Figure 2. As for manual driving related papers, the average number of papers published

per year from 2009 to 2015 was 23. After 2015, this number was reduced to 19. In 2018, the number of papers in automated driving surpassed that in manual driving.

Secondly, by investigating published surveys [73, 98] and based on our research experience in this area, we first grouped the papers into two major categories, manual driving and automated driving and then identified the topics under these two umbrellas as illustrated in Figure 3 in each year. These topics were identified by examining all the papers in the review by two of the authors and further discussions were conducted among all the authors to finalize the uncertain ones. The major research topics are summarized below:

- A) Manual driving (78.3%):
- 1) UIs, including visual, auditory, haptic and gestural, and multimodal (36.2%),
 - 2) Driver state, including distraction, cognitive workload, and emotion (14.1%),
 - 3) Methodology, including new design, measurement techniques, and test protocols (9.4%),
 - 4) Augmented reality (AR) and head-up displays (HUDs) (5.4%),
 - 5) Navigation (4.0%), and
 - 6) Others, including eco-driving, infotainment, user acceptance, cultural differences, etc. (9.1%).
- B) Automated driving (21.7%):
- 1) Takeover (5.1%),
 - 2) Trust and acceptance (4.3%),
 - 3) Interacting with road users (2.5%),
 - 4) UIs (2.5%),
 - 5) Methodology (1.4%), and
 - 6) Others, including collaborative driving, buses and trucks related, non-driving related tasks (NDRTs), remote driving, driving styles, legal issues, cultural differences, deskilling, driver states, and so on (5.8%).

THE DEVELOPMENT OF AUTOUI RESEARCH TOPICS

Manual Driving

User Interfaces

Haptic and Gestural Interfaces: Haptics and gestures are considered as control tools and inputs that allow drivers to interact with the vehicle using tactile sensation and body movements. Examples of haptic and gestural interfaces in the vehicle include warnings, assistance, and infotainment systems. Some haptic interfaces are concerned with increasing the awareness of drivers to prevent accidents by providing vibration in the steering wheel or in the driver seat. Other haptic interfaces, such as touch screens, are now commonly utilized in vehicles for various control and infotainment systems [2, 15, 80, 81, 111], because they can reduce the number of physical controls in vehicles to create a cleaner and less cluttered design [111], and they are often easy to learn and use even for novice users [163]. For example, Pitts et al. [111] compared the user experience (UX) of three types of touch screens and found that resistive touch screens were the

least preferred due to its slow responsiveness while capacitive touch screens were most liked.

Despite the popularity of touch screens in vehicles, Large et al. [81] found that there were strong linear relationships between visual demand of interaction tasks through a touch screen and Fitts' index of difficulty. Therefore, it is extremely difficult to design a touch screen interface without visual attention during driving. Harrington et al. [47] pointed out that visual attention demanded by touch screens included two elements, i.e., 1) the inherent visual demand by the task itself and 2) the driver's motivation to engage visually with the touch screen. Despite various research endeavors to minimize the visual demand of touch screens, long glances larger than 2 seconds still exist, especially by the driver's motivation. Tunca et al. [152] investigated glance-free operating on touch screens and found those with haptic feedback resulted in significantly fewer errors than those without.

Recently, a number of novel technologies that aim to minimize such visual demand are proposed. For example, mid-air gestures with ultrasound haptic feedback seem promising. Simple and natural gestures in the midair are used as an input to control the touch screen. Ahmad et al. [1] proposed to reduce visual demands by predictive touch using mid-air gestures. However, without feedback, such touchless control tended to be less effective. In order to provide haptic feedback, the principle of acoustic radiation is used to transmit haptic forces to the skin tissues when ultrasound is reflected. Therefore, mid-air gestures with ultrasound haptic feedback do not need accurate hand-eye coordination, reducing mental and visual demands of the task on the driver. For example, Harrington et al. [47] directly compared a virtual mid-air gestural interface with a traditional touch screen and found that it was particularly advantageous, when mid-air gestures combined with ultrasound haptic feedback, to reduce the off-road glance time and the number of long glances. Researchers also explored which type of air-gestural interactions is optimal. For example, May et al. [95] identified the lowest subjective workload of air gestural interactions using participatory design while Rümelin et al. [124] found the most user preferred modulation duration and frequency of mid-air ultrasonic feedback. However, currently, it is still difficult to recognize complicated mid-air gestures. For example, simple V gesture resulted in 96.26% - 99.62% accuracy while other gestures (e.g. swipe left/right, clockwise/counterclockwise rotations) had significantly worse performance [134, 135].

Auditory Interfaces: Auditory interfaces are used in vehicles as communication and warning tools to manage drivers' attention. Examples include speech dialogue systems, recognition systems, and advisory and warning systems.

First, many researchers proposed speech dialogue systems to reduce drivers' distraction during the interaction process. As an example, Gable et al. [40] proposed an advanced auditory information system for search tasks on drivers' phones to im-

prove their driving performance. Kennington et al. [64] presented an incremental spoken dialogue system to adapt the delivery of speech to the road conditions to minimize distraction. Large et al. [79] investigated the cognitive workload of drivers while interacting with an audio system based on natural languages and a delayed digital recall task resulted in highest levels of cognitive demand and visual distraction. Terken et al. [147] presented an auditory service system for handling emails and texting to keep drivers' eyes on the road.

Second, voice recognition systems can automatically understand the intentions of drivers using machine learning methods and thus they are easier to use. For example, Hackenberg et al. [44] compared a natural language understanding (NLU) system with a command and control speech system to overcome voice recognition problems by monitoring the lane change deviation of drivers. The participants preferred the NLU system as it could lead to efficient communication with the vehicle without commands. However, such results were obtained using a Wizard-of-Oz method and the recognition accuracy of such systems is the key not to annoy drivers.

Third, many researchers also made use of auditory interfaces to advise or warn drivers in the vehicle. For example, Fagerlönn et al. [29] tested different strategies to notify drivers and found that shifting the radio sound (from being equally played in both ears to the right ear only) was especially effective and tolerable to warn drivers. In addition, Orth et al. [107] introduced an assistance on demand system that provided audio feedback by considering the time gaps to enter an intersection, which reduced drivers' workload and increased driving performance. Wang et al. [157] found that drivers had positive attitudes toward a 3D auditory traffic information system that helped them focus their attention on the roads with auditory icons. Later, Wang et al. [158] investigated drivers' needs of a 3D auditory traffic information system and the participants liked the concept of providing auditory information of the blind spots.

Visual Interfaces: Visual interfaces are mainly used to guide drivers' visual attention for a safe drive. Light displays based on ambient LEDs form a major part of visual interfaces to inform or warn drivers of road conditions by changing their patterns or colors. Specifically, they can be used to provide collision warnings, lane change decision aids, visualizing road users and obstacles, displaying speeds, and directing and visualizing gazes [90]. For example, Löcken et al. [90] proposed a decision aid system to show the distance of an approaching vehicle for a safe lane change using two LED light patterns. LED lighting patterns were also useful in modulating drivers' speeds and drivers had positive experience with the right patterns, such as an adaptive speed modulation mode [100, 59]. Another important function is that LED patterns can effectively guide drivers' attention, such as sequential LED illumination to identify targets [128], visual calibration with LEDs to predict targets [150], and informing malfunctioned ADAS with a group of LEDs in the driver's peripheral view [78]. Furthermore, Trösterer et al. [151] made

use of LED visualization for collaborative driving tasks between the driver and the co-driver.

Multimodal Interfaces: Multimodal interfaces provide multiple modes of interaction between the driver and the vehicle, such as auditory, haptic, and visual as discussed above. They have proved to reduce driver distraction, mental workload, and reaction time [85].

First, multimodal interfaces are widely used to warn drivers in emergency situations, when a single modality, such as visual, tends to be less effective. This is due to the fact that unlike auditory and tactile information, visual information is not gaze-free and it often combines with auditory, tactile, or both to enhance its effectiveness. For example, visual and auditory warnings were used for a pedestrian alert system to reduce collision risks [99]. Other studies utilized multimodal interfaces to indicate the urgency of the warning, including auditory and tactile in [113] and auditory, visual, and tactile in [112, 136]. They all discovered that such multimodal interfaces received higher ratings of urgency, quicker response time, but more driver annoyance at the same time.

Second, a good combination of complementary modalities can provide a powerful means of interaction to reduce drivers' workload and distraction. For example, Fujimura et al. [39] used a pointing mechanism combined with a 3D HUD to obtain information about the outside environment to minimize visual distraction. Ohn-Bar et al. [105] built a hand gesture-based visual UI to predict if the driver or the passenger was performing the task. Consequently, it could encourage gaze-free interactions without interfering the interactive experience with the infotainment system. Shakeri et al. [134, 135] investigated multimodal feedback with mid-air gestures to reduce driver distraction. Among all the tested feedback, non-visual feedback, especially auditory and haptic feedback were most effective at reducing visual distraction. However, many multimodal interfaces tend to be user, task, or environment dependent and it can potentially affect other secondary task performance while improving the performance of the driving task, such as menu navigation using haptic and auditory cues [144] and infotainment interaction with both gestures and audios [110] in touch screens. Nevertheless, multimodal interfaces are flexible in nature and are able to address individual differences and changing environments. For example, Roider et al. [123] pointed out that among the combinations of visual, auditory, and gestural input modalities, the driver had the freedom to select the method of interaction depending on the driving situations and personal preferences.

Driver States

Distraction: Distraction impacts driving performance and is a major factor in automotive accidents. Among the studies reviewed here, three major NDRTs lead to distracted driving, including interacting with handheld devices (e.g., cell phones, iPods), the infotainment system (e.g., navigation and entertainment systems), and stimuli outside the vehicle (e.g., traffic signs). With the prevalence of mobile phones, it is imperative to understand how these devices distract drivers.

Studies have shown that it is more distracting to conduct complex NDRTs than simple ones. For example, handheld-based texting impaired driving performance more than speech-based texting [48] and auditory address entry led to better driving performance than a visual entry method using both Samsung S4 and iPhone 5s [96]. Drivers also can adapt to the demands of the driving environment when conducting NDRTs. For example, Kun et al. [74] found that it was more demanding to interact with a portable music player (i.e., iPod) on a highway than in a city.

Another major source of distracted driving is interacting with the infotainment system, especially when visual demands are required, such as interacting with touch screens. For example, Kujala et al. [72] examined potential in-vehicle tasks that led to visual distraction and found that all the visual-manual tasks did, especially text entry and scrolling. In order to alleviate the visual distraction of text entry, voice recognition-based text entry was found to be significantly less demanding than handwriting and keyboard text entries [69]. However, such results depended on a user-friendly and accurate voice recognition system. Besides, notifications in the vehicle pose another threat to safe driving, especially when the primary driving task is cognitively demanding. For example, Rajan et al. [116] indicated that both auditory and visual notifications caused distraction while Kujala et al. [70] found that GPS displays introduced less distraction.

Compared with the distraction within the vehicle, those outside the vehicles were less studied. In this aspect, Hurtado and Chiasson [58] examined driver distraction of unfamiliar road signs using eye tracking data and found that increased time and interpretation errors occurred with reduced speeds compared with familiar road signs. Hoekstra-Atwood et al. [54] studied involuntary distractions by introducing irrelevant stimuli in a driving simulator and they made use of the inhibitory control of drivers to these stimuli and found that more distraction lay in drivers with low inhibitory control.

Cognitive Workload: Workload can be considered as the amount of demand placed on a person and the effort required to complete a task and cognitive workload emphasizes the amount of mental demand required to perform a certain task, which can vary based on the task [97]. Mehler et al. [97] pointed out that the (cognitive) workload can be very different due to individual differences (e.g., gender, health status, and technical experience), time constraints, and driving conditions. In the AutoUI proceedings, researchers mainly focused on how to assess drivers' cognitive workload using different techniques, such as physiological measures, self-reported measures, and vehicle-related measures. For example, Kun et al. [75] proposed a weighting function of pupillary light reflex to evaluate drivers' cognitive workload and Schnergass et al. [129] assessed drivers' workload based on both physiological data and subjective ratings. Similarly, Reimer et al. [118] examined the effect of different levels of cognitive workload on physiological arousal while Demberg

et al. [23] evaluated drivers' cognitive workload using synthesized German sentences with fine-grained linguistic complexity. These techniques demonstrated the development in measuring drivers' cognitive workload. Taylor et al. [145], on the other hand, presented the Warwick-JLR Driver Monitoring Dataset, in which multiple types of data were collected to assess drivers' cognitive workload, including physiological measures, self-reported NASA TLX (Task Load Index) data, and vehicle telemetry data.

Emotion: Driving is a complicated task and various situations involved in driving can elicit emotions and they in turn can place both positive and negative effects on driving. In AutoUI proceedings, studies were conducted to detect emotions using different types of techniques, such as physiological data, driving contextual data in order to inform drivers. For example, GPS data (e.g., congestion, stopping, braking, turning, and acceleration) [120, 154] and heart rate variability [120] were used to predict driver stress levels so that they could change their route plan accordingly. In addition, researchers also attempted to elicit a certain type of emotions from drivers so as to improve their driving performance. Fakhrosseini et al. [30] investigated the effect of music in relieving drivers' stress and found that happy or sad music lead to better driving performance. Hsieh et al. [57] showed that adding an angry tone to a hands-free phone conversation increased drivers alertness to decrease distraction during driving. Furthermore, by understanding driver behaviors under different emotions, corresponding UIs can be designed to alleviate the negative influence or reinforce the positive influence of such emotions on driving. Jeon et al. [62] investigated the negative effects of anger and fear on driving and suggested an adaptive UI to alert the driver when they were in such emotional states to improve the driving performance.

Methodology

Methodology papers in the manual driving domain tend to focus on different stages involved in vehicle UI design, including data collection and analysis, measurement, design methods, and test protocols. Of all the methodology papers in AutoUI conferences, those related to design methods accounted for 50% in the past decade. General Motors incorporated contexts in-vehicle interaction design back in 2010 [42]. Meschtscherjakov et al. [101] proposed three qualitative in-situ methods as a compromise between laboratory and field studies. From the ideation point of view, Kern and Schmidt [65] presented a design space by examining existing UIs from over 100 vehicles while Schroeter et al. [131] investigated new ideas for future cars based on urban informatics to balance safety and joy. Different evaluation methods at the early stages of interface design were also proposed, including a keystroke level model [130], a theater-system technique, and a model-base attention prediction system [130, 33]. Another systematic design method explicitly emphasized was human-centered design (HCD) and its application to vehicle (interface) design. For instance, the HCD approach was used to identify user needs of mobile devices in

future vehicles [16], to develop a driving simulator using virtual reality for vehicle rapid prototyping [5], and to enhance vehicle interior design [6].

Another important stream of studies proposed new measurement models and techniques for UI design. For example, Shahab et al. [132] presented techniques on how to measure personal driving values, Körber and Bengler [66] presented UX measures using momentary interactions, Green [43] presented a set of driving performance measures and statistical guidelines, and Miura et al. [103] proposed a quantitative method to measure driver's visuospatial workload.

In vehicle design, from a regulatory perspective, National Highway Traffic Safety Administration (NHTSA) and International Organization for Standardization (ISO) play important roles in both regulating and standardizing various tests. However, some of the test protocols are either outdated or oversimplified so that researchers in the AutoUI community proposed new methods. For instance, Large et al. [82] tested a touch screen interface against the NHTSA Eye Glance Testing using a driving simulator, Kujala et al. [71] evaluated a navigation system based on NHTSA criteria for acceptance of electronic devices and tested the visual demand of driving tasks against the NHTSA task acceptance, and Pournami et al. [115] discussed the sample size needed in the Occlusion Test Protocols of NHTSA and ISO to evaluate the visual demands of drivers. These studies significantly advanced different aspects of the standardization from the governmental/organizational point of view. Hess et al. [51], on the other hand, proposed a reference model to guide UI design from the perspectives of manufacturers, suppliers, and software tool developers.

Augmented Reality and Head-up Displays

Recently more advanced information systems, such as AR, are used in vehicles. Unlike virtual reality, AR is able to render a variety of high-quality digital information to real-world objects in the drivers' line of vision in real time [164], which offers a seamless environment to improve navigation, visual search tasks, and so on. First, we observe that AR is widely used in the vehicle to help drivers navigate by providing virtual objects, such as vehicles, pedestrians, hazards, and landmarks, and it has proved helpful compared to traditional navigation aids. For instance, Bolton et al. [11] found that an AR landmark-based navigation system significantly outperformed other systems and Topliss et al. [148] discovered that AR-based lead vehicle was helpful in navigating complex junctions. In addition, Bark et al. [8] combined an AR navigational system with a see-through 3D display to help participants make safe turn decisions earlier with depth perception.

Second, while investigating its usefulness in the vehicle, AR is often paired with a HUD and compares it with traditional displays, such as head-down displays (HDDs). Unlike HDDs located usually in the center of the vehicle's control panel, a HUD presents virtual information in the driver's natural line of sight, which can reduce the number and duration of the

driver's glances off the road. Therefore, HUDs have been increasingly used in vehicles so that drivers can maintain their views on the road while acquiring information needed to improve driving performance. Shahrir and Kun [133] indicated that the HUD-based AR navigation tended to work better than HDD navigation aids as it did not draw attention away from the road. Depth information was also added to help improve driving performance and experience by providing guidelines to correctly place HUD AR imagery for drivers [91] and combining volumetric displays with AR [87]. On the other hand, Haeuslschmid et al. [45] pointed out that it was important to display only the necessary or preferred information for different drivers when AR information was expanded to be displayed on the whole windshield.

Third, when HUDs are not paired with AR, i.e., they display virtual information without registering with real objects, it tends to produce mixed results when they are compared with other displays (e.g., HDDs). For example, projecting the texting output using HUDs on the windshield was found to improve driving performance [155] while HUDs were also found to increase visual complexity and clutter [138]. In addition, although participants preferred HUDs, they made more errors in the text- and grid-based visual search tasks [139] and worse driving performance compared to auditory displays [159]. Hence, more research is needed to understand when HUDs offer useful information.

Automated Driving

Takeover

The Society of Automotive Engineers (SAE) defines driving automation with 6 levels from no automation (Level 0) to full automation (Level 5) [125]. While we are advancing from the current partial automation (Level 2) to higher levels of automation, drivers are becoming increasingly out of the control loop, which makes it difficult for them to take over control when the system reaches its limit (e.g., automation failure, adverse weather) [28], especially in conditional automation (Level 3). However, it is challenging to ensure a safe takeover transition, due to different factors involved, such as takeover lead time, warning types, and situational awareness of the driver. Mirnig et al. [102] reviewed control transition interfaces in automated vehicles and identified challenges associated with their design. Among many, one important aspect emphasized by AutoUI researchers was warning displays at the takeover request. For example, in order to convey takeover urgency levels, Politis et al. [113] designed a variation of rhythm, roughness, and intensity of auditory warnings and later Politis et al. [114] combined auditory, visual, and tactile warnings. In order to enhance drivers' situation awareness, Borojeni et al. [13] designed a new steering wheel to communicate the direction of steering with haptic feedback, Borojeni et al. [12] used an auditory warning and an LED strip to show the direction of steering, and Telpaz et al. [146] provided vibrotactile feedback on the driver seat to inform the position of the surrounding vehicles.

Another important issue is how to offer an explanation at the time of takeover requests, which can improve driver situation awareness and takeover performance. Walch et al. [156] proposed a cooperative interface with an explanation for takeovers both in visual and auditory forms, letting the driver accept or reject the proposition. Faltaous et al. [31] provided continuous feedback of system reliability to facilitate takeovers. The timing of the takeover requests is also critical to ensure takeover performance. For example, Wintersberger et al. [162] found that participants had better takeover performance when requests were issued between tasks rather than within tasks. However, this may not be guaranteed during emergency situations. Maurer et al. [94] proposed another concept for the vehicle to take over manual driving when imminent accidents were likely to happen. However, the participants viewed it rather differently. Thus, more research is needed to explicitly simplify the autonomy of the vehicle.

Trust and Acceptance

Acceptance of automated driving can be defined as drivers' willingness to adopt vehicle technologies. While there are many factors that determine the driver's acceptance, one of the most critical factors and also most frequently studied ones is probably trust in highly automated driving. This is due to the nature of highly automated driving that allows drivers to be involved in NDRTs and requires them to take over control from automated driving at the same time. The uncertainty and vulnerability involved in the system are often not transparent and thus the level of trust tends to fluctuate, which affects their acceptance of highly automated driving.

Researchers identified different factors affecting trust and acceptance of automated driving, including human-related, automation-related, and environment-related [126]. Human-related factors, including age, experience, knowledge about automated driving, were investigated in AutoUI proceedings. For example, Rödel et al. [122] showed that the more the driver had experience in the automated driving, the higher his/her acceptance was. Frison et al. [37] found that each age group had different types of needs and UX of automated driving depending on the contexts, which called for UX concepts that support universal design and mass personalization [165] at the same time. Among automation-related factors, AutoUI researchers mainly investigated system reliability, uncertainty, and UIs. For example, Helldin et al. [50] showed that drivers trusted in the automated vehicle more when they were provided with uncertainty information of the system. Faltaous et al. [31] examined how to communicate system reliability to drivers to improve driver trust, experience, and acceptance in highly automated driving. In addition, Gang et al. [41] designed a sonifying system to convey system perception of contextual events, which did not change driver trust, but improved their situation awareness. Environmental factors, such as reputation of original equipment manufacturers (OEMs), and automotive manufacturers, were studied. For example, OEM reputation did not facilitate user trust and acceptance, and they should present system capabilities and limitations realistically to prevent over-trust and distrust

[35]. Furthermore, trust in automation was also influenced by people's knowledge about the technology, the company's brand name, and how this technology fit in daily life [117].

Therefore, it is important to consider all three aspects to design automated driving systems that can create an appropriate level of user trust in automation. Lee et al. [83] suggested three design aspects to build trust in the automated system, including (1) continuous evaluation of the performance of the vehicle by the driver, (2) providing the driver with information about the external and in-vehicle driving situations, and (3) expanding the role of the vehicle to incorporate emotional interactions with the driver.

Interacting with Road Users

Designing a communication interface to express intentions between automated vehicles and other road users, especially pedestrians and bicyclists, is a key element for safety. Interacting with road users can be divided into formal interactions (e.g., braking lights, turn signals, and warning lights) and informal interactions (e.g., body expressions) [32]. In the AutoUI community, researchers mainly focused on how to interact with pedestrians both informally and formally. Beggiato et al. [9] explored the influence of the vehicle size, speed and the pedestrians' age on their accepted gaps and estimated time to arrival while Zimmermann and Wettach [166] investigated the influence of vehicle motion behavior on pedestrians' emotion and decisions. Others explored the role of external displays in interacting with pedestrians. For example, Li et al. [89] proposed external display warnings with different colors to indicate three levels of safety-related information (alert, dangerous, and safe situations). Chang et al. [17] developed an interface by adding eyes to the headlights, which helped pedestrians make correct and quicker street-crossing decisions. Another study done by Currano et al. [21] highlighted regional differences of how pedestrians interacted with automated vehicles, which helped predict pedestrian behavior and inform customized design strategies for future automated vehicles in different regions.

User Interface

UI in automated driving plays a critical role in interacting with the driver. According to NHTSA [24], the automated system should inform the driver whenever the system is (1) functioning properly or experiencing a malfunction (2) engaged in the automated mode or it is not available, and (3) requesting a control transition from automated driving to manual driving. The AutoUI researchers mainly investigated interfaces related to the transition of control (see Section Takeover) and to informing the driver of system status and environmental situations as well as their influence on drivers. For example, hue, as a color-based variable, was most favored to convey uncertainty information involved in automated driving among 11 proposed AR-based displays [76] and the onboard touchscreen was preferred to a smartphone display to show vehicle status and ride information [106]. In addition, van Veen et al. [153] showed that peripheral lights increased drivers' situational awareness while performing

NDRTs and Chuang et al. [18] found that professional truck drivers responded differently from non-professional ones to auditory interfaces using EEG data across test environments.

Methodology

It is often challenging to conduct studies for automated driving due to the unavailability of automated vehicles, especially for SAE Levels 3-5. The majority of the studies related to automated driving were conducted using driving simulators in the laboratory (e.g., [53]) or a Wizard-of-Oz method (e.g., [21]) on the road. In order to improve the validity of simulator-based studies, Hock et al. [53] provided guidelines and suggestions in eight aspects for automated driving. Schieben et al. [127] presented the theater system technique based on a Wizard-of-Oz method to design and evaluate interaction behavior in highly automated vehicles. Other studies involve measurement and design techniques. For example, Forster et al. [34] suggested seven improvements on the existing measurement techniques related to evaluating UIs in automated driving and Heymann and Degani [52] considered modeling, analysis, and design issues of automation features.

CHALLENGES, TREND, AND FUTURE DIRECTIONS

From Driving Assistance to Driving Automation

In manual driving, we have seen that the research focused on how to design UIs to provide assistance through various systems, such as touchscreens (e.g., [111]) and mid-air gestural interactions (e.g., [134, 135]), speech dialogue systems (e.g., [40]), auditory and LED-based warnings (e.g., [59]). While these systems can greatly improve driving performance and experience by providing important information about the driving tasks, such as navigation, object search, emergency notifications, and infotainment, they tend to complicate the interaction process. This has a direct influence on the complexity of the UIs that the driver has to interact with various provided functions. For example, mid-air gestures with feedback greatly reduced the off-road glance time, but the drivers had to use a set of different gestures for the system to recognize various commands with imperfect accuracy [134, 135]. Hence, how to improve the usability of such driving assistance systems is still one of the challenges in UI design.

We also see that new types of UIs have emerged and evolved quickly with both driving support and high-quality infotainment experience. For example, speech dialogue systems can handle emails and texting during driving [147] while keeping the driver's eyes on the road, and LED patterns can indicate issues with ADAS [78]. These systems look easy to use for some users, while confusing others. This forces the designers to consider a large number of users with different qualifications and technical backgrounds. Hence, it is challenging but imperative to design and test such systems with consideration of the target users with different qualifications. Among many, one of the potential trends that can address this is conversational interfaces enabled by increasingly advanced artificial intelligence, where drivers can give commands to the vehicle (e.g., call Walter and open the sunroof).

With the transition from manual driving to automated driving (SAE Level 3 and above) in progression, many of the driving assistance systems are being replaced by driving automation. For example, the mid-air gesture system [134, 135] and the speech dialogue systems [147] mentioned above may not be useful at all in an automated vehicle, because the driver now can be decoupled from the driving task and can fully focus on NDRTs. In this situation, the major challenge is whether the driver is willing to take an automated vehicle in the first place, i.e., trust in automated driving. It is well-known that an appropriate level of trust is essential for the driver to interact with the system successfully in automated driving [26]. The recent and ongoing trend is to identify various factors influencing trust in automation and how they can be manipulated in order to obtain an appropriate level of trust as shown in Section Trust and Acceptance. This is also recognized by studies outside the AutoUI proceedings. For example, Lee and See [84] identified individual, organizational, cultural, and contextual factors that influence trust in the process. Hoff and Bashir [55] integrated both personal and system-related factors of trust by examining extensive literature. Schaefer et al. [126] identified three types of factors influencing trust in automation, including human-related, automation-related, and environment-related.

These identified factors offer guidelines to create an appropriate level of trust in UI design. However, neither of them addresses the practical issue of estimating driver trust in real time in order to manage and build an appropriate level of trust dynamically. Previous studies [3, 63] have attempted to predict trust using experience or self-reported data using dynamic models. Nevertheless, it is intrusive and not practical to request the driver to report his/her trust level during the human-machine interaction process. Computational models have been proposed to estimate trust in other domains. For example, Hoogendoorn et al. [56] proposed a trust computational model based on the personal attributes of users. Leichtenstern et al. [86] found that eye gaze and heart rate patterns were associated with different levels of trust. In this respect, we need to figure out how to make use of computational models to predict driver trust in real time in order to calibrate driver trust in automated driving. Other researchers take another perspective on trust that trust is extremely difficult to measure as a psychological construct while it is among many factors that determine the performance of human-machine interaction in automated driving [25]. It is ultimately the decision making preceding the interaction process determines the behavior involved in the interaction. Therefore, the challenge is shifted to predict the decisions rather than trust preceding the interaction process.

Another important outcome when driving assistance systems are shifting to driving automation (SAE Level 3 and above) is that drivers/passengers in the vehicle may not pay attention to other road users or there may be no drivers or passengers at all in the vehicle, which makes it difficult to interact with other road users. Under such circumstances, the challenge is

how to design interfaces to communicate with other road users effectively and efficiently, especially vulnerable pedestrians and bicyclists. Currently, many researchers (e.g., [89, 17]) capitalize on external displays to communicate the intentions of the vehicle. The challenge is how to make sure that such displays are able to convey its intentions directly, simply, and unambiguously. In order to do so, text messages, such as “Walk” and “Don’t Walk” are effective [20]. However, this might not work for those who do not understand the language (e.g., foreigners). Then, other possible signs are used, including colors [89] and eye contacts [17]. However, studies have shown that cultural differences can influence the interaction between automated vehicles and pedestrians (e.g., [21]). Hence, cultural-specific symbols and metaphors should be avoided. The external displays also need to work in poor- or strong-lit conditions and adverse weather conditions (e.g., snow and fog) for different types of road users (children, the elderly, and the handicapped). It thus calls for standard tests and both government agencies (e.g., ISO, NHTSA) and the automotive industry should collaborate.

From Distraction to Takeover and NDRTs

Manual driving is a complex and dynamic task that relies on drivers’ attention that can sometimes be shifted from the primary task of driving to perform NDRTs that may lead to accidents. Despite the distraction involved, drivers are still interacting with mobile devices (e.g., accessing to social media, texting, and calling) (e.g., [40, 96]) and in-vehicle infotainment systems (e.g., [69, 72]) while driving. Therefore, the major challenge is how to minimize such distraction during driving in order to maintain safety. Many researchers make use of the multiple resource theory [160], which asserts that people have several different pools of information processing resources and tasks involving different pools of cognitive resources can be performed concurrently. For example, auditory address entry resulted in lower workload compared to the visual one [96] and voice-based text entry was less distracting than typing and handwriting [69]. However, the levels of distraction are still not equivalent to driving without performing these auditory tasks for the majority of the drivers [93]. Others introduce new technologies into the vehicle to mitigate distracted driving. For example, voice recognition-based interaction can automatically understand driver intentions [44, 69], mid-air gesture recognition with ultrasound feedback can reduce both mental and visual demands without accurate hand-eye coordination [1, 134, 135]. Other researchers come up with techniques to restrict drivers’ interaction with mobile devices by recognizing their activities [46, 121]. These methods all borrow the power of artificial intelligence to proactively sense, predict, reason, and act to minimize driver distraction. Thus, the success depends on the maturity of the artificial intelligence-based technology in terms of its prediction accuracy, reasoning capability, and UX in the vehicle in various conditions.

While the research focus is shifting from manual driving to automated driving, the safety concerns also shift from minimizing the distraction of performing NDRTs to improving

takeover performance. The influence of various factors on takeover performance has been studied in the AutoUI community, including warning displays (e.g., [113, 114, 146]), takeover time (e.g., [28]), and NDRTs (e.g., [119]). The primary challenge is how to help drivers resume manual control successfully when they are engaged in NDRTs. From the warning displays’ point of view, multimodal alarms are often used. For example, visual, auditory, and/or tactile warnings are combined to show different levels of urgency with improved takeover performance (e.g., [12, 114]). Another direction is to provide a multi-stage takeover request. For example, in a two-stage takeover request, a warning (1st step) and an alarm (2nd step) will be provided and drivers can get prepared to take over control at the first warning and have additional time to resume situation awareness [27]. However, more research is still needed to address the optimal warning modalities and timing associated with multi-step takeover requests across different types of drivers.

NDRTs are one of the benefits brought by highly automated driving. For one thing, performing NDRTs can prevent drivers from underload and boredom to help resume control. For another, drivers can be fully engaged in NDRTs, reducing situation awareness and increasing reaction time during the takeover transition period. One possible research direction is to automatically intervene the NDRT if the driver is performing it on some electronic devices (e.g., pause, warning displayed on top of the NDRT) combined with verbal traffic situations that explain the reason for the takeover request. However, for other types of NDRTs, a viable solution is probably to have a monitoring system on the driver and whenever the driver’s attention or alertness is beyond designed thresholds, the system will notify the driver to re-orient his/her attention. However, such a monitoring system may disrupt the NDRT experience. It is suggested that the driver should have the ability to prioritize NDRTs over non-urgent messages [162]. Yet, more research is still needed to maintain safe control transitions and improve driving experience while performing NDRTs at the same time in highly automated driving.

Currently, design for NDRTs seems secondary given the focus on the distraction. However, in fully automated vehicles, the challenge is how we should redesign the vehicle interior to accommodate the interplay among safety, productivity, and hedonics. In this sense, the human-centered design approach mentioned in the next section is useful to identify the user needs of NDRTs of different types of vehicles, including sedan, SUVs, buses, and trucks. Researchers have used contextual observation to elicit user needs in public vehicles [109]. For long-haul trucks, a mobile office seems reasonable while for commuting vehicles, other fun and engaging NDRTs are promising (e.g., AutoGym [67] and gamification [141]). In this aspect, another possible direction is to redesign the interior of the vehicle so that the driver is able to reconfigure the interior to facilitate specific NDRTs.

From UI Design to UX Design

UI design is an important task as evidenced by the number of studies in manual driving. Various types of UIs were addressed in manual driving, such as communication using auditory interfaces (e.g., [44]), navigation using AR-based interfaces (e.g., [133]), touchscreen-based interfaces (e.g., [152]), and decision aids using LED-based interfaces (e.g., [90]). These types of UIs address individual aspects of driver states (e.g., cognitive workload, distraction, emotional states (see Section User Interface)) in different scenarios in manual driving, which may not be able to address the holistic UX involved in driving. In order to support holistic UX involved in driving, the main design methods proposed in the AutoUI community include context design [42], qualitative in-situ methods [101], and theater-system techniques [33] to capture the automotive contexts. For example, the qualitative in-situ methods identified three design spaces, including the driver, the front seat passenger, and the rear seat passenger spaces, to address different areas of the vehicle [101].

When we are transitioning from manual driving to automated driving, a holistic UX design method is even more challenging due to the fact that many human-related issues are still not solved while automated driving systems are mainly technology-centered. Hence, how to address the holistic UX problem from the human-centered design (HCD) perspective is a grand challenge for automated driving systems. The HCD approach aims to make the system not only useful, usable, but also pleasurable to use by concentrating on the human users, their needs and requirements, and thus is more promising to bring automated driving systems to the society with a wider acceptance and quicker adoption rate. Many researchers have adopted the HCD approach to tackle human-related issues in automated driving, such as exploring user needs for NDRTs [109] and mobile devices in automated vehicles [16], and acceptance and UX of different autonomy levels of vehicles [122]. These studies show the potential of HCD. And yet, it is still challenging to instill an appropriate mental model of how automated vehicles work into users under various conditions [84]. For example, an automated vehicle may switch between levels of automation in different areas (e.g., from SAE Level 3 on highways to SAE Level 2 on urban roads) and the user needs to switch his/her mental model accordingly in order to interact with the vehicle successfully. In addition, to what extent the user needs to know how the automated driving system operates is another question so that he or she will not be overwhelmed by the information provided [19]. Therefore, the system needs to be designed to be transparent to support information exchange to guide users to form a correct mental model to support rational decision making under uncertainty and complexity. Furthermore, the HCD approach should also support user hedonics with different use cases of automated driving. In order to so, NDRTs should be well explored to support safe and fun driving experience. In the AutoUI proceedings, examples include AutoGym [67] and gamification [141] that shed lights upon the novel driving experience.

Another potential challenge in improving UX is how to address special groups of users in automated driving. For example, how to address the handicapped in automated driving services when there is no driver for assistance? How to respond to users with health issues/emergency during automated driving? How to address motion sickness in automated driving when drivers become passengers? UIs and vehicles need to be designed to accommodate various situations in order to improve driving UX.

Simulator Studies vs. Naturalistic Studies

Driving simulators have been widely used in the AutoUI community to study driver behavior because they provide a safe, reproducible, and controllable environment for the study at hand. This trend is evidenced by the fact that 52.3% of all the studies in AutoUI proceedings were conducted in a driving simulator while 16.3% were conducted in a naturalistic environment. For example, studies related to UI design and evaluation (e.g., [134, 135]), distracted driving (e.g., [96]), takeover (e.g., [146]), trust in automated driving (e.g., [41]), interacting with pedestrians (e.g., [89]) were conducted in driving simulators. Such simulator-based studies not only reduce the risks of the participants during driving but also reduce the cost of running the studies. Another important reason of this trend is that automated vehicles are still not easy to access as the technology is not entirely mature yet while driving simulators (e.g., using virtual reality) can generate different prototypes for UX studies at the early stage of the design rapidly (e.g., [5]).

However, the main challenge of simulator studies is that driving simulators may not be able to provide ecologically valid driving experience, which raises the question of transferability, reliability, and validity of the study results [10], due to the motion sickness involved, low fidelity, and low costs and risks of making mistakes in driving simulators. For example, Helland et al. [49] showed that simulator sickness led to slower driving, Blana [10] pointed out that the physical and behavioral reliabilities should be tested (e.g., motivation and distraction of the subjects), and Hock et al. [53] called for considerations of various aspects in order to design a valid simulator study.

A good compromise between driving simulators and naturalistic driving is to use a Wizard-of-Oz study running on the road, in which some functions of the vehicle is simulated. Such a configuration can create a realistic environment as long as the participants are not aware of the magic wizard. It offers both the participants and the experimenter more free expression and systematic control at the same time than a driving simulator [7, 22]. Good examples employed such a technique include [7, 21, 44, 127] in AutoUI proceedings.

CONCLUSIONS

This paper reviewed the research evolution from manual to automated driving over the last ten years of the AutoUI conferences. We identified various topics and described their development related to manual driving and automated driving. Among them, the main topics for manual driving include

UIs, driver states, AR and HUDs, methodology, and the main topics for automated driving consist of takeover, trust and acceptance, interacting with road users, UIs, and methodology. Over the last decade, we witnessed that the research focus is transitioning from manual driving to automated driving and during this transition, we discussed the potential challenges, trends, and future directions of this research.

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