ABSTRACT

CLARK, HALLIE ELIZABETH. Limited Self-Driving Vehicle Automation: Age Differences in the Takeover of Vehicle Control, Engagement in Non-driving-related Activities and Opinions of the Technology. (Under the direction of Dr. Jing Feng, Dr. Anne McLaughlin, and Dr. Billy Williams.)

High-level vehicle automation has been proposed as a valuable means to enhance the mobility of older drivers, who experience age-related declines in many cognitive functions that are vital for safe driving. Resent research has aimed to investigate methods to assist a driver with regaining control of the vehicle during takeover, which is the transition from automated to manual driving or from a higher level of automation to a lower level Understanding the behavior of drivers during the takeover will allow for further development of this advanced technology. This study aims to observe driver behavior during the takeover, including their performance following two different notification intervals, as well as their engagement in non-driving-related tasks, in order to provide further understanding for development of the highly automated vehicle technologies. In this study, 17 younger drivers (age 18-35, mean age = 19.9 years) and 18 older drivers (age 62-81, mean age = 70.4 years) completed simulated driving with limited self-driving automation in a simulated environment, and were encouraged to freely decide when and how to engage in voluntarily chosen non-driving-related activities during simulated driving with conditional automation. Video recordings of participants' engagement in non-driving-related activities were coded during analysis. The effect of age, level of activity-engagement and the takeover notification interval on vehicle control performance during the takeover were examined by comparing between the high and low engagement groups in younger and older drivers, across two takeover notification interval conditions. Additionally, drivers' opinions towards the automated vehicle technology were assessed with a survey. It was found that both younger

and older drivers engaged in various non-driving-related activities during the automated driving portion, with distinct preferences on the type of activity for each age group (i.e., while younger drivers mostly used an electronic device, older drivers tended to converse). There were also significant differences between the two age groups and between the two notification intervals. In general, older drivers benefited more than younger drivers from the longer interval in terms of response time to notifications. Voluntary engagement in non-driving-related activities did not impair takeover performance in general, although there was a trend of older drivers who were more engaged in non-driving-related activities braking harder than those with low activity engagement during the takeover. And finally, the results of the survey indicated that older drivers were more concerned with potential usability issues of highly automated vehicles.

Limited Self-Driving Vehicle Automation: Age Differences in the Takeover of Vehicle Control, Engagement in Non-driving-related Activities and Opinions of the Technology

by
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BIOGRAPHY

Hallie E. Clark is a doctoral student within the Human Factors and Applied Cognition program at North Carolina State University. Prior to beginning graduate school, Hallie received her Bachelor of Science in Psychology at North Carolina State University. During her undergraduate career, Hallie experienced many different majors and a breadth of courses before being exposed to human factors and subsequently pursuing a career in the field. Hallie's primary goal throughout her graduate career has been to bridge the gap between the transportation industry and the human sciences behind the development. Her work has been recognized by the industry, indicated by receipt of the Megan Cornog Highway Safety Scholarship in 2015, as well as obtaining a research assistantship at the Institute of Transportation Research and Education throughout most of her graduate career. Outside of school, Hallie enjoys expressing herself creatively through her artwork as well as hanging out with her 8 going on 2 year old pup, Dalton.

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INTRODUCTION

In 2013 nearly 33,000 people died and 2.31 million people were injured in motor vehicle crashes (NHTSA, 2014a), with the rate of fatal crash involvement per mile travelled increasing by age starting in the mid-60s (Insurance Institute for Highway Safety, 2013). There are 37 million older drivers in the US, making up 17% of all drivers (FHWA, 2013), and the amount of adults over age 65 on the roads is reported to continue to steadily increase (McDevitt & Rowe, 2002). Older drivers are at a "greater risk for crashes due to medical conditions, medications, and functional impairments" (Wang & Carr, 2004, pp. 143). In addition, older drivers are also more susceptible to distractions (Young, Regan & Hammer, 2007). Driver distraction is one of the most significant causes of injuries and fatalities, and based on estimates gathered in 2012, driver distraction can account for 10% of fatalities and 17% percent of injuries (NHTSA, 2014b). While a solution to decreasing driver distraction has been to educate drivers and eliminate distractions by regulation, there is no possible way to entirely eliminate distraction. With this accepted realization, the industry has been tirelessly working on a resolution that would allow individuals to still travel, yet greatly reduces the impact of distraction. Autonomous vehicle (AV) technology has been proposed as potential solution to this issue. However, it is not clear whether AV technology, with various levels of automation, may mitigate or encourage driver distraction. With more automation and less manual operation, the effect of vigilance increases, thus potentially encouraging driver distraction (Norman, 2015). Furthermore, although AV technology has been said to provide an option for safe mobility of older adults (Reimer, 2014), older drivers

may have different interactions with limited self-driving, and their needs may differ from those of younger drivers, therefore emphasizing the need to analyze the age differences in these interactions and needs.

Levels of Vehicle Automation

Automated vehicles (AVs) are described by the National Highway Traffic Safety Administration (NHTSA) as vehicles in which "at least some aspects of a safety-critical control function (e.g. steering, throttle, or braking) occur without direct driver input" (NHTSA, 2013, pp. 3). There are five total levels of vehicle automation (Table 1, descriptions of the levels are quoted from NHTSA (2013), pp.4-5) established by NHTSA. These levels provide separation between the technologies which can be useful for guiding discussions with stakeholders and for focusing research efforts.

Extensive research has been conducted on the lower levels (0-1) of automation. For example, vision-based lane-recognition systems (Apostoloff & Zelinsky, 2003; Risack, Klausmann, Krüger, & Enkelmann, 1998) and centimeter-level vehicle-positioning systems (Wang et al., 2005) have been established to enhance lane keeping in vehicles. In recent years, the research focus has begun to shift towards Levels 2 through 4, focusing on features such as adaptive cruise control and collision avoidance (Vahidi & Eskandarian, 2003; Moon, Moon, & Yi, 2009). The higher levels of automation will require NHTSA and the Department of Transportation (DOT) agencies to develop policies, laws and regulations surrounding the many aspects that are involved with a vehicle at this stage of automation. The development of regulations will need to be based on a good understanding of the

Table 1

Levels of Vehicle Automation

Level	Description
0	**No Automation**: The driver is in complete and sole control of the primary vehicle controls, is responsible for monitoring the roadway and for safe operation of all vehicle controls. Examples include systems that provide only warnings (e.g. forward collision warning, lane departure warning, blind spot monitoring) as well as systems providing automated secondary controls such as wipers, headlights, turn signals, and hazard lights.
1	**Function-Specific Automation**: The driver has overall control of the vehicle, is responsible for safe operation, but can choose to cede limited authority over a primary control (e.g. cruise control). In addition, the vehicle can automatically assume limited authority over a primary control (e.g. electronic stability control) or can provided added control to aid the driver (e.g. dynamic brake support in emergencies). At this level, each function that is automated must operate independently from one another.
2	**Combined Function Automation**: The driver is responsible for monitoring the roadway, safe operation, and is expected to be available for control at all times and on short notice. At this level, the vehicle may have at least two primary control functions which are automated and designed to work in unison to relieve the driver of control of these functions. Examples include a vehicle which has adaptive cruise control operating in combination with lane centering. The system may relinquish control with no advanced warning.
3	**Limited Self-Driving Automation**: The driver may cede full control of all safety-critical functions under certain traffic or environmental conditions. Under these conditions, the driver can rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to the driver's control. This system is expected to provide drivers with a sufficiently comfortable transition time (i.e. providing a warning before driver needs to regain control). An example would be an automated car (self-driving) which can determine that it can no longer safely control the vehicle (i.e. it senses an oncoming construction zone) and therefore signals to the driver that it will transition control back to manual. This level of automation does not require the driver to constantly monitor the roadway.
4	**Full Self-Driving Automation**: In this level, the vehicle is designed to perform all safety-critical driving functions and monitor the roadway conditions for an entire trip. It's anticipated that the driver will input destination and navigation, but will not be expected to be available for control at any time during the trip.

Adapted from NHTSA (2013), pp. 4-5

technology, its users, and user-technology interaction. This will be essential for the automotive industry to progress in their productions and development. Among the unexplored topics around autonomous vehicle (AV) technology, NHTSA (2013) has identified three areas where research is urgently needed; these areas are a) human factors research, b) AV system safety, and c) development of AV system requirements. This study will primarily be relevant to the field of human factors. In this research field for AV technology, important topics include driver to vehicle interaction, allocation of vehicle control functions (e.g., division of labor, transitions, and override requirements), driver acceptance, training, and other various tools for evaluation (NHTSA, 2013).

Market Projection of Autonomous Vehicle Technology

The automobile industry has set the pace for the implementation of Levels 3 and 4 automation by stating their mission to have a product ready by 2020 (Los Angeles Times, 2015; Nissan, 2015). Recently, Delphi Drive has made headlines by having their autonomous car called Roadrunner complete at 3,400 mile journey from San Francisco, California to New York City, New York. Their vehicle is equipped with advanced technologies such as forward collision warnings, lane departure warnings, collision mitigation, and integrated radar and camera systems (Delphi Automotive PLC, 2015). A commonality among each company that is aiming to introduce Levels 3 and 4 automation is that those setting the timeline and operating the vehicles are engineers and individuals who are highly familiar with the technology, this is seen with the Delphi Drive where the Roadrunner completed its cross-country drive but was accompanied by 6 trained engineers. It's doubtful that the engineers

who were highly familiar with the vehicle would make common human errors such as pushing the wrong button, attempting to override, or crashing the system by incorrect inputs, which may be seen from regular drivers who are less experienced with the autonomous vehicle (AV) technology.

Regardless of the market projection, the implementation of higher levels of AV technology is predicted to take years to reach full saturation. It's estimated that this technology will not be at its completed implementation stage (where everyone who wants the technology has the technology) until after the year 2060 (Litman, 2014). Although this seems a long time, this estimation is appropriate considering with the number of years taken to deploy various technologies that are commonly found in vehicles today, such as air bags (25 years), automatic transmissions (50 years), and navigation systems (30+ years, still hasn't reached full saturation) (Litman, 2014). The implantation projections of AVs as described by

Table 2

Autonomous Vehicle Implementation Projections

Stage	Decade	Vehicle Sales	Vehicle Fleet	Vehicle Travel
Available with large price premium	2020s	2-5%	1-2%	1-4%
Available with moderate price premium	2030s	20-40%	10-20%	10-30%
Available with minimal price premium	2040s	40-60%	20-40%	30-50%
Standard feature included on most new vehicles	2050s	80-100%	40-60%	50-80%
Saturation (everybody who wants it has it)	2060s	-	-	-
Required for all new and operating vehicles	-	100%	100%	100%

* "-" is used when an estimation could not be made
Reproduced Table 6 from (Litman, 2014), p.11

Litman (2014, Table 6, p.11) can be viewed below in Table 2. Litman states that without

mandates, the deployment will most likely follow the pattern of automatic transmissions,

which took nearly five decades to reach market saturation, in fact, some motorists still choose

manual transmissions due to personal preferences and cost savings (2014).

Recent Research on Human Factors of Autonomous Vehicle Technology

Due to the accelerated timeline for autonomous vehicle (AV) technology, researchers

are attempting to analyze key issues when considering the higher levels of automation,

particularly in levels 2 and 3. Some examples of the current research being conducted for the

development of assistive programs include vehicle route planning and path mapping,

placement of sensors, vehicle display units, collision avoidance (Bergholz, Timm, &

Weisser, 2000), long range radars and GPS tracking (Los Angeles Times, 2015), vehicle to

vehicle communication (NHTSA, 2014), and gesture control (BMW Group, 2015). One

project looked at driver engagement and disengagement in the driving task using eye tracking

(Merat, Jamson, Lai, Daly, & Carsten, 2014). This study compared the effectiveness of

transferring control back to the driver, either in fixed intervals, or when the driver was

reportedly disengaged. The results of this study showed that drivers responded better when

control was shifted to them after a fixed interval of time, as opposed to when they were given

control in random intervals, as established by using the eye tracker to determine when their

visual attention was taken off of the roadway ahead (Merat, Jamson, Lai, Daly, & Carsten,

2014). Another project by the same research group examined drivers' performance when

manipulating the workload in highly automated and manual driving. This study found that in

a natural driving hindrance (such as a traffic accident) drivers had relatively equal performance in both automated and manual driving, however when an unrelated task was implemented drivers were not able to perform as well in the automated driving. It's hypothesized that this is due to limited attentional allocations. (Merat, Jamson, Lai, & Carsten, 2014). The pioneering projects provide guidance for future development and research in regards to limited self-driving vehicle technology.

Among the research, there is a focus on creating a seamless transition from computer controlled driving to driver controlled driving for the driver with the development of assistive technologies such as the warning function before the takeover (i.e., the transfer of control to the driver after automated driving). A driver needs to expect the transition, understand the current environment condition and the vehicle state, in order to successfully take control of the vehicle. According to NHTSA (2013), a warning should be provided to the driver in an AV prior to any transition or takeover. This warning to takeover interval is essential to provide drivers enough time to re-engage in driving. Despite the importance, very little research surrounding the takeover has been conducted. Merat and her colleague (2014) used eye tracking to monitor driver disengagement and initiate the takeover (Merat et al., 2014). Lorenz, Kerschbaum, & Schumann (2014) applied augmented reality to increase the situational awareness in the transition. By implementing augmented reality to increase situational awareness, Lorenz et al. (2014) have established two methods of augmented reality to notify drivers of the safety of their path by using a green (safe) and red (unsafe) highlighted roadway. In level 3 limited self-driving vehicle technology, understanding the

takeover is an integral part of its success. Further research is needed to determine the most effective warning interval before the takeover, as well as to understand how drivers perform (e.g., speed, lateral position) during a takeover with varying intervals and workloads. In addition, analyzing the age differences in the takeover is needed considering the increasing amount of older drivers on the road (McDevitt & Rowe, 2002).

While companies like Google and Delphi can log many miles of autonomous driving without any crashes attributable to the technology, the same results need to occur for the individual who knows nothing about the technology and its inner workings. Like any other product, limited self-driving vehicle technology needs to be developed and sold to the public in order to propel the saturation of the technology. It's no secret that AV technology will likely provide many benefits such as reduced crashes (NHTSA, 2013), and reduced congestion (Anderson, Nidhi, Stanley, Sorensen, Samaras, & Oluwatola, 2014). Another common thought is that the vehicle will allow more free time for the driver to work, read a book, or make phone calls, converting the driver to more of a "passive supervisor" while the vehicle is driving itself (Reimer, 2014). However, like with any technology, there are potential problems associated with AV technology. From a driver's perspective, there are issues surrounding reliability of the system, trust of the system, and use of the system. Some considerations that have been identified when a user is involved with automation are concerns with system error (Sarter & Woods, 1997), over-reliance (Parasuraman & Riley, 1997), under-reliance (Endsley & Kiris, 1995; Kaber, Onal, & Endsley, 1995), and communication errors (Hollands & Wickens, 1999). These concerns have been researched,

and investigated, and they all have implications with human to automation. For example, when a user is overly reliant on automation there is a risk for both omission errors (i.e., human overlooks an error in the system) and commission errors (i.e., human follows an incorrect directive due to automation) (Miller, Funk, Goldman, Meisner, & Wu, 2005). It's imagined that individuals will weigh both the costs and the benefits associated with the technology, and this will have a great impact on the adoption of AVs. As in many situations, the public's acceptance of AV technology will be the driving force behind the adoption of the technology.

In an effort to gauge the public's opinion surrounding AV technology, a survey was conducted by Schoettle and Sivak (2014). The respondents' of this survey were evenly distributed from ages 18-60, with each decade making up roughly 20-25% of the total respondents in this age range. Approximately 8% of the respondents were over the age of 60. Regardless of the vast age range, this study did not look at age differences within the responses. This survey examined drivers' familiarity with the technology, concerns associated with the technology, and general opinions on AVs (e.g., How concerned are you about riding in an autonomous vehicle). Contrary to claims made that there would be less crashes (NHTSA, 2013), and traffic would be less congested, therefore reducing travel times (Anderson, Nidhi, Stanley, Sorensen, Samaras, & Oluwatola, 2014) with AV technology, the survey results indicate that only 16.5% of individuals felt it was very likely that traffic would be less congested as well as 13.7% believed that it was very likely for reduced travel time. The survey also raised awareness to other issues which are often overlooked by industry

stakeholders, such as concern with commercial vehicles being automated (78.9% were at least moderately concerned), system being hacked (68.7% were at least moderately concerned), or self-driving vehicles not performing as well as a human driver (66.8% were at least moderately concerned). A majority of the responses collected for this survey reported being moderately or very concerned with issues surrounding AV technology. These concerns can cause issues in the performance with AV technology, as well as the implementation of AV technology. This survey highlights drivers' concerns about AV technology, as well as starts a conversation for how to facilitate the adoption of this technology. While the conversation exists, having a tangible performance that's associated with the survey responses will increase the validity of the concerns that are raised.

Many benefits are predicted for AV technology, nevertheless there will inevitably be limitations such as resistance to the technology and improper use of the systems. With all technological advances, the possible limitations should be placed at the forefront for research and investigation. These limitations and issues that could arise from use of AVs must be explored so that the technology can adapt to any observations or issues that result from use by the average driver, including younger, middle-aged and older drivers.

Factors that Impact the Implementation of Autonomous Vehicle Technology

When considering autonomous vehicle (AV) technology, it's important to note the various factors that could impact the implementation of the technology. This study has identified several key factors which could prove to be significant in the shift to AV technology, in addition, these factors could hinder the shift to AV technology from both a

wide-scale social aspect and individual performance. These factors include acceptance of the

technology, attentional differences, emotion related decision making, the interval which the

warning is administered (notification interval), and the engagement in non-driving-related

tasks. Based on relevant research, these factors differ with age, therefore it's hypothesized

that these factors could be used to explain any age differences found in the performance with

AV technology. The following sections will provide an overview of each factor along with

the research in relation to driving literature. In the end of this section, the age differences

within these factors and establish the necessity of analyzing the performance in AV

technology between age groups will be summarized.

Acceptance. A key factor to consider when beginning to utilize AV technology is the

acceptance of the technology. Understanding the acceptance of the technology on a small

scale can provide insight as to how the public will respond to the technology as a whole. As

with any technological advancement, the general acceptance is not immediate. For example,

automatic transmissions were introduced in the 1940s, and yet the market still has not

reached full saturation (Litman, 2014). Gaining the acceptance of the public will be critical to

the success of the technology, and this can be done by focusing on the individual.

In order to gain acceptance, the benefits of the technology need to be clearly defined

and these benefits need to be reliable to the user. If a benefit of AV technology is said to be

reduced congestion and quicker travel times, the statement of benefit needs to be tested and

proven prior to the introduction of AV technology. Issues will inevitably arise when an

average driver is operating this technology, and these issues could impact the reliability of

the stated benefits. Observing the driver behavior when interacting with this technology will provide insight into how to prepare the individual, therefore prepare the public.

　　Attention. Another key factor to consider when developing AV technology is the different attentional requirements between present-day driving and the operation of AVs. Considering that this technology is new, we are not fully aware of how drivers will act when interacting with AVs. For example, a driver may engage with their cellular device, read a book, or fall asleep when the vehicle is driving itself and no action is required from the driver. Drivers suffer from poorer performance when they are at a low alert level (e.g., when they are drowsy) or distracted (e.g., using their phone, passengers, or roadside activity). When distracted, drivers tend to have less control of their speed and headway distance (Rakauskas, Gugerty & Ward, 2004; Strayer & Drews, 2004); and the lateral position on the road (Engström, Johansson & Östlund, 2005; Reed & Green, 1999). Distracted drivers also have reduced awareness of surrounding traffic and abrupt events (Kass, Cole & Stanny, 2007). Individual differences, including age differences, lie within our attentional resources (Hunt, Pellegrino, & Yee, 1989) and our susceptibility to distractions (Engle, Kane, & Tuholski, 1999). These differences emphasize the necessity for proper development and training methods in order to ensure that each individual is provided the best opportunity to perform successfully. Driving requires a high level of situation awareness, and "acquiring and maintaining situational awareness becomes increasingly difficult as the complexity and dynamics of the environment increase" (Endsley, 1995). Depending on driving experience and attentional capacities, some drivers may be more impacted by the increasingly difficult

driving environment. Therefore, growing complexity and dynamics of the environment (e.g., increasingly heavy traffic, entering a construction zone) further complicates the issue of individual differences in the available attentional resources to interact with AV technology.

Emotion. In addition to attentional differences, emotions can play a major role in the driver's ability to operate the vehicle. Emotions significantly impact how individuals react to various situations. Research indicates that positive emotions lead to better task performance than negative emotions (Jeon, Walker & Yim, 2014), likely due to the risky behavior that is a result of negative emotions (Mano, 1994). Drivers experience a range of emotions during their daily drives, but considering the impact of negative emotions is more detrimental to performance, it's these emotions that are the main focus of this overview.

Negative emotions such as anger and frustration (e.g., road rage) are commonly seen in drivers during daily driving. Additional negative emotions that can arise when driving include fear, anxiety, and discomfort, all of which may result in negative consequences in driving performance. In driving literature, fear is commonly associated with anxiety and nervousness (Jeon et al., 2014). Anxiety has been proven to affect the attentional capacity by narrowing the focus of spatial attention (similar to tunnel vision) and in general, causing difficulty in focusing attention (Jeon et al., 2014). This could potentially cause issues considering driving requires attention to the entire surrounding environment that expands across an extended visual area with controlled concentration on the driving task for a prolonged period of time. In addition, nervousness can have a high impact on performance in using AVs. When an individual experiences a new situation, increased levels of nervousness

are typical. However, in relation to driving, nervousness can cause similar results in concentration deficits as anxiety (Jeon et al., 2014). In fact, nervousness has been considered to be one of the most dangerous driving states, as it can increase the occurrence of human errors and tendencies of driver distraction (Li and Ji, 2005).

The impacts of emotions on driving is a relatively recent topic being explored, however considering the different requirements that driving an AV will have, the impacts of emotion on this operation must also be considered. If anxiety narrows the attentional focus, this could be detrimental when operating an AV, which would likely require the ability to have a large field of focus (as in monitoring the environment).

Notification Interval. A major technological factor in AV technology is the notification that will be administered before the takeover. NHTSA has established a method of safety which has been to require a "sufficient warning" prior to takeover. Understanding the necessary notification interval for takeover (e.g., user gains control after vehicle self-driving) and release of control (e.g., user gives control to the vehicle) is essential to create safe transitions (NHTSA, 2013). Sufficient time to re-engage in the driving task will ensure drivers are prepared for a transition and enhance drivers' perceived control of the technology.

Non-driving-related Activities. With an increasing amount of automation, drivers are more likely to engage in non-driving-related tasks, such as reading an email or watching a video (Merat et al., 2014; Carsten, et al., 2012; Saxby et al., 2013). While research on driver distraction clearly suggest the detrimental effects of distraction on driving performance (for a review, see Young & Regan, 2007), investigations of the effect of engagement in non-

driving-related activities during highly automated driving remain sparse and existing findings have been paradoxical.

Some evidence points to a detrimental effect of engaging in non-driving-related tasks on driving with conditional automation (Louw, Merat & Jamson, 2015; Merat et al., 2012; Zeeb et al., 2016). For example, Merat and her colleagues (2012) used a verbal task to simulate phone conversations during autonomous driving. The researchers found the degradation on responding to a critical event while the drivers were being engaged in the verbal task. In line with this, Zeeb et al (2016) found that although drivers can return their hands to the steering wheel equally quickly, the quality of takeover (e.g., lateral position control) is significantly poorer when drivers engaged in non-driving-related activities such as writing an email, reading the news, or watching a video.

However, other studies suggest the opposite. Neubauer et al (2012) examined the effect of cell phone use on manual and automated driving. The researchers found that using a cell phone impaired drivers' braking response in manual driving. However, the drivers were faster in braking when using a cell phone compare to no secondary task during automated driving. This raises an important notion that engagement in non-driving-related tasks in highly automated driving may combat with the loss of alertness due to the cognitive underload associated with high level automation (Ma & Kaber, 2005; Young & Stanton, 2002). Along this line, Miller et al (2015) observed significant drowsiness when drivers were asked to overseeing the vehicle system during simulated automated driving. The level of drowsiness is greatly alleviated when drivers engaged in a non-driving-related activity such

as reading text or watching a movie. Engagement in these non-driving-related activities was found not to impair driver performance on takeover of vehicle control (Miller et al., 2015). Due to the intricate interplay among mental workload, driver boredom, alertness, and driving performance, it is not yet fully clear how non-driving-related activities impact driving with conditional automation, or whether the impact differs between younger and older drivers.

Situations such as takeover of vehicle control in highly autonomous driving could be cognitively demanding. To achieve an effective takeover of vehicle control (e.g., with minimal change in speed and lane deviation), a driver needs to exercise high sensitivity to a visual or auditory notification of the takeover, fast processing of perceptual information presented inside and outside the vehicle, accurate recognition of potential hazards, efficient choice of the correct response, and prompt motor action to the situation. Takeover of vehicle control in driving with conditional automation could be more challenging for older drivers due to age-related cognitive declines. Such challenge may further intensify with the impact of these aforementioned factors.

These factors play significant roles in how well AV technology will be accepted and used by younger drivers, middle-age drivers and older drivers as well as their willingness to engage in non-driving-related tasks. Significant age differences in acceptance, attention and emotion can lead to largely different interaction with the autonomous driving technology among the age groups. This could be due to the fact that older adults typically use modern technology less than younger adults (Eisma et al., 2004). Older adults are also more likely to fear modern technology as well as possess a fundamental lack of trust for the technology that

is newly introduced (Eisma et al., 2004). This combination of unfamiliarity and fear will

most likely result in great anxiety and poor performance in high-level automation driving.

Beyond age differences in emotions towards technology, a major factor that could cause

reluctance to transitioning to autonomous driving for older age groups is the association they

make with driving. Older individuals associate their freedom and independence with driving

(Lee, Cameron, and Lee, 2003), therefore removing the act of driving by implementing level

4 AVs could cause older individuals distress and feelings of stereotype threat. This could

ultimately cause older adults to be less accepting of the technology. In addition, age-related

declines in attentional capacity could make it more challenging for older drivers to interact

with AV technology. Age-related decline has been found in the deployment of attention

(Ball, Beard, Roenker, Miller & Griggs, 1988; Sekuler & Ball, 1986), attentional switching,

and visual search (Parasuraman & Nestor, 1991; Plude & Hoyer, 1985). When driving,

declined attentional ability could lead to poor driving performance. For example, an analyses

of police reports revealed that "driver inattention" is cited as the cause for most accidents

involving older adults (Shinar, Zaidel, & Paarlberg, 1978). In addition, older adults have

longer reaction times (Hultsch, MacDonald, & Dixon, 2002), and have more variable

reaction time in a task (Christensen et al. 1994; Morse 1993). The age differences in reaction

time could have significant implications for the usefulness of the warning. Furthermore, in

the event of a takeover, an older driver who was engaged in non-driving-related activities

could experience a higher mental workload than a younger driver, therefore could

demonstrate substantially different driving behaviors compared to those of a younger driver.

This was indeed observed in a recent effort to compare younger and older drivers'

performance in takeover while driving in no, medium and high traffic (Körber et al., 2016).

In the study, although older drivers in general performed as well as younger drivers in all

traffic conditions, older drivers exerted compensatory driving behaviors such as using the

brake more frequently and maintaining a longer time to collision from other road users

(Körber et al., 2016).

Ultimately, these factors provide insight into the potential differences between

younger and older drivers when interacting with AV technology. The factors described

above, and the limited research surrounding human behavior and AV technology, lead to

several questions which the proposed research aims to address.

Research Questions and Hypotheses

This research aims to examine how drivers handle a takeover during which the

control of the vehicle is transferred to the driver from the automated system (level 3

automation; NHTSA, 2013, and if a driver's performance on the takeover is influenced by (1)

the driver's age, (2) how much time in advance the driver is informed of the takeover, and (3)

their engagement in non-driving-related tasks. Non-driving-related activities were coded by

frequency and duration of activities (i.e., electronic device use, communication, eyes off

road) identified in video recordings of participants. Performance during takeover is measured

by average speed, standard deviation of lane position, brake input, throttle input, steering

wheel angle, and notification response time. In addition, this research examined drivers'

opinions towards autonomous vehicle (AV) technology using a survey before and after experiencing simulated driving with limited self-driving automation.

Hypothesis 1: Driving performance in the takeover zone (the area which extends 400 feet following the takeover, depiction of this zone can be seen in Figure 2b) will get significantly better with more experience. This will be indicated by drivers having a more consistent speed after the takeover, less variance in the lateral position, and a shorter time to takeover.

Hypothesis 2: A longer warning interval will lead to better performance in the takeover zone. A longer warning interval allows for drivers to have more time to re-engage in the driving task. This will be indicated by average speed, standard deviation of lane position, brake input, throttle input, steering wheel angle, and notification response time, compared between the two warning intervals (7.5 s and 4.5 s).

Hypothesis 3: Older drivers will perform worse than younger drivers in the simulated drive. There will be more variance in speed and lateral position, as well as a longer time to takeover.

Hypothesis 4: Engagement in non-driving-related activities could impact the drivers' performance during a takeover.

Hypothesis 5: Older drivers will express more negative opinion towards AV technology, as compared with younger adults.

Hypothesis 6: Survey responses collected prior to the simulated driving that indicate negative feelings towards AV technology (i.e., participant indicates they do not like the technology and do not feel comfortable using it) are negatively correlated with performance in the takeover zone. Poorer performance will be indicated by more varied speeds and lateral positions during takeover.

METHOD

This study aimed to examine the effect of age, notification interval, and engagement with non-driving-related activities on driver performance on the takeover of vehicle control in highly automated vehicle technology. Additionally, the study analyzed participant's opinions towards automated vehicle technology with the administration of a survey both before and after the experiment. Driver performance was measured using driving simulation, and video recordings were analyzed and coded following the experiment to determine the engagement with non-driving-related tasks.

Participants

18 older participants (age range: 62 – 81 years, mean age: 70.4 years, 11 men, 7 women) and 17 younger participants (age range: 18 – 35 years, mean age: 19.9 years, 11 men, 6 women) completed the experiment. All participants had normal or corrected-to-normal vision, held a valid driver's license, and were active in driving (e.g., drove at least once a week) at the time of experiment participation. Younger participants were recruited from the University's undergraduate introductory psychology course, and were compensated with course credits. Older participants were gathered from local communities including the

Kiwanis club of Raleigh (a volunteer organization) and the North Carolina State University

Older Adult Research Participant Pool. Old participants were compensated at a rate of $12/h.

No participant in this study reported experiencing simulator sickness, likely due to the pre-

experiment screening of prior motion sickness experience, frequent breaks during the

experiment, and the design of the driving environment with minimal components (e.g.,

turning at intersections) that could cause simulator sickness. As a result, all recruited

participants completed the study and were included in the data analysis.

Materials

Experimental Room Setting. The experiment took place in a controlled laboratory

setting. The experiment room was dimly lit with black drapes covering the walls behind the

simulator. This is done to eliminate the perception of static texture on the wall behind

dynamic simulation which can induce simulator sickness.

Survey Adapted from Opinions Concerning Autonomous and Self-Driving Vehicles.

Participants completed a questionnaire before and after the simulated drive. This

questionnaire (Appendix A) has been adapted from the survey of opinions concerning

autonomous and self-driving vehicles (Schoettle and Sivak, 2014). This survey will be used

to measure participants' knowledge of and experience with level 3 AV technology, and their

opinions toward level 3 AV technology.

Simulated Driving. Participants completed the experiment using a console version of

STISIM Drive 3, which is comprised of a steering wheel, driving pedals, and a driver seat.

Driving simulation was displayed using three adjacent 42-inch television screens which

extended a 135º field of view (Figure 1a). The graphics were presented on each display at the

resolution of 1920×1080 pixels, and driving performance measures were recorded at a rate of 60Hz.
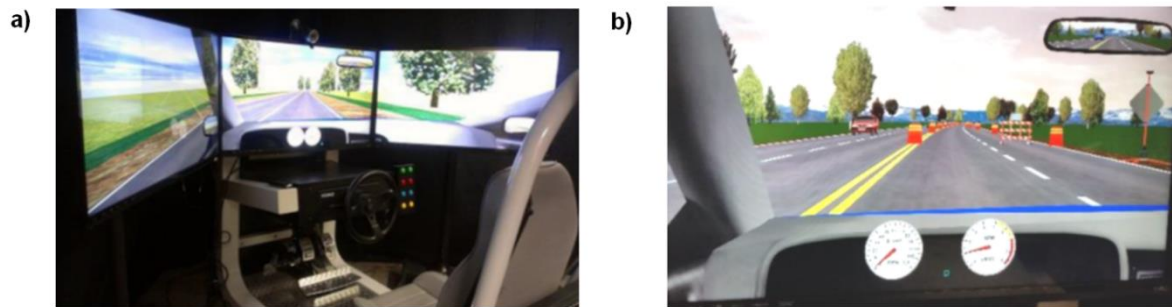

Figure 1. a) Setup of the STISIM Drive 3 Simulator used in this study. b) An example driving scene (entering construction zone) in the simulated scenario of driving with conditional automation.

During driving simulation, every participant first completed a practice drive, consisting of stop signs and two transitions between autonomous driving (computer in control) and manual driving (driver in control). The participant then completed three drives which contained both autonomous driving sections and manual driving sections designed to create a feeling of operating a limited self-driving vehicle. During each drive, there were four transitions from autonomous driving to manual driving (takeovers) and four transitions from manual driving to autonomous driving (release control). Therefore, there were 12 takeovers and 12 release of controls in total across the three drives. The set speed during the autonomous portion was 72.42 km/h (45 mi/h), which is also the advised speed limit during the manual portion. Each drive is a total of 10.5 km, containing four manual zones (designed as construction zones) which expanded a distance of 0.64 km per zone, and four autonomous driving zones which expanded either 1.80 km or 2.41 km per zone. These distances were

selected based on time, with each autonomous drive lasting 1.5 minutes (1.8 km) or 2

minutes (2.41 km). The reason for using two distances of autonomous driving rather than one

was to reduce the predictability of the timing of takeover and thus encourage natural

disengagement from driving during the autonomous zone. The 12 manual zones were

randomly distributed across the three drives, with the restriction of four manual zones in each

drive. The order of the three drives are counterbalanced between participants.

The simulated drive resembled a four lane rural highway. The three drives are

identical except the appearance of the manual zones. A small number of oncoming vehicles

were placed throughout the simulated driving environment to create a more naturalistic

environment, as well as provide the participants with realistic distractions. The placement of

the oncoming vehicles was designed to not overload the participant. During the autonomous

portion, the computer controlled both the speed and lane position of the vehicle. By

definition, these two features alone are representative of the level 2 AV (i.e., at least two

primary control functions in a vehicle are automated); however, given there are no vehicles

travelling the same direction as the driver's vehicle and no sudden objects occur on the

roadway during autonomous driving, the vehicle is able to mimic a level 3 limited self-

driving vehicle.

The manual driving portions are designed as construction zones, in order to provide a

reasonable justification as to why the vehicle can no longer drive itself in the environment.

There are six different construction zones that are uniquely designed. Each construction zone

appeared twice, one for each auditory notification interval. During manual driving,

participants were responsible to control all longitudinal and lateral aspects of the vehicle (e.g. speed and lane position).

Two auditory notifications were used, each of which indicate an upcoming takeover or release of control. The auditory notification for an upcoming takeover consists of two beeps, first of 400 Hz and then a successive beep of 350 Hz. The auditory notification of the
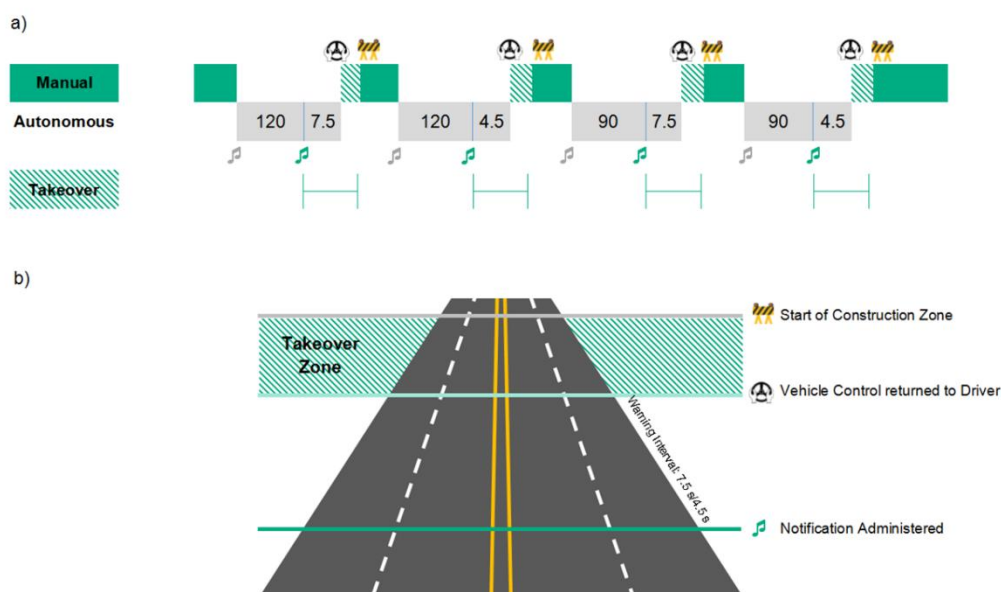

Figure 2. a) An example driving session with alternation between automated and manual zones displayed sequentially. The number presented inside each box notes the average duration of the period in seconds (in the experiment, these durations were randomly selected values around the average). The length of each grey or green block is not proportional to the time duration it represents. Each grey music note represents a notification to release control (i.e., transition of control from the driver to the vehicle), and each green note stands for the notification to takeover (i.e., transition of control from the vehicle to the driver). There was a notification interval of either 7.5 s or 4.5 s (indicated in the grey boxes) after each notification to takeover. The green striped section within the manual driving section represents the takeover zone, which started from the point that the vehicle control was returned to the driver to the start of the construction zone. A takeover attempt by the driver (e.g., put hands back on the steering wheel) could take place at any time after the takeover notification was presented. b) A more detailed depiction of events in a takeover from a driver's perspective.

upcoming release of control consists of two beeps as well, the first 350 Hz and then 400 Hz. For the purpose of this study, the takeover (and therefore the warning before the takeover) will be the main emphasis.

This notification is presented at two intervals: one occurs 152.4 m (7.5 seconds) before the takeover, and the other occurs 91.4 m (4.5 seconds) before the takeover. These intervals were selected considering the choice of visual notification interval in an earlier study on takeover (10 s; Merat et al., 2014) and general recommendations of auditory notifications (3-5 s; Gray, 2011; Scott & Gray, 2008). During the notification interval, the vehicle remained in the automated mode until the mandatory return of control took place (Figure 2b). Therefore, vehicle speed remained constant during this period. After each takeover, participants had 121.9 m to re-engage in driving (i.e., resume full control of the vehicle) before a construction zone starts, this portion is defined as the takeover zone.
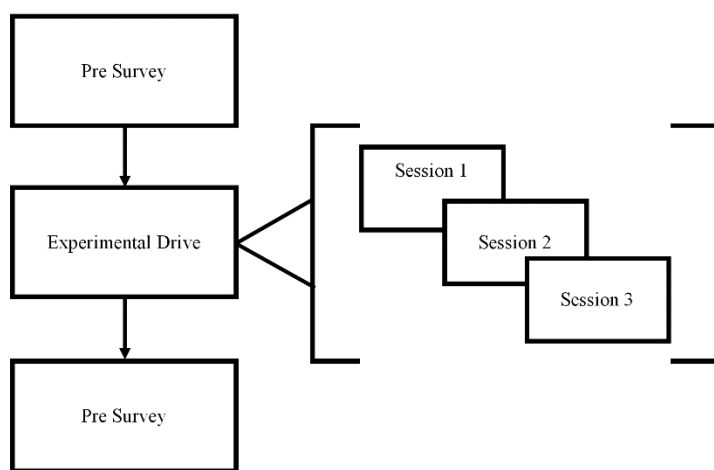
Procedure

An overview of the procedure can be seen in Figure 3. After signing up for the experiment, each participant completed the pre-survey through Qualtrics Survey Software (Provo, 2011) prior to their experiment appointment.

Figure 3. Procedure overview

This program is an online survey administration tool which allows easy distribution of surveys to participants, and organizes the responses. The pre-survey included the demographic questionnaire information as well as the survey for opinions on AV technology (Schoettle & Sivak, 2014). Participants also completed the Simulator Sickness Questionnaire (Kennedy, Lane, Berbaum, & Lilienthal, 1993) prior to signing up for the experiment to assist their decision in their participation in simulated driving.

During the laboratory session, participants first received the informed consent form. After consent is received, participants had the opportunity to become familiar with the STISIM Driving Simulator, and make any necessary adjustments to their seating position to improve comfort in the simulator. Once the necessary adjustments are completed, participants received a briefing of the simulated driving task and the notification sounds (the warning for takeover, and the warning for release of control). Once the participants understood the instructions, they practice simulated driving during a practice drive. Participants were allowed to repeat this practice if they desire. After the practice drive, the participants completed three experimental drives. Participants were encouraged to take breaks between each drive. Following the final drive, participants were asked to complete the post-survey. They were instructed that it was the same adapted opinions concerning autonomous and self-driving vehicles survey (Schoettle & Sivak, 2014) they had previously taken, but to complete it based on their experiences up until that point (therefore including their experience in the drive).

RESULTS

Driver performance at the takeover was analyzed by driving performance measures collected by the STISIM Drive 3 simulator, as well as analyzation of video recordings and self-report survey responses. Performance was analyzed by multiple mixed-between repeated measures ANOVAs, observing the effect of age, activity level and notification interval on drivers speed, lane position, brake, throttle, steering wheel angle, and response time. Level of engagement was assessed by the frequency and total duration of each non-driving-related activity, and used as a within-subject factor for analysis between high and low activity levels. Groups were determined based on a median split. Furthermore, analysis of engagement in non-driving-related activities was analyzed using a MANOVA comparing the two groups (low and high activity) as well as age differences. In continuation with the analysis, survey data was analyzed with multiple mixed between-within repeated-measures ANOVA, comparing pre and post drive as well as age differences.

Engagement in non-driving-related activities

Based on the total duration of engagement in all non-driving-related activities, a median split was performed in the younger and older driver groups. Among the 17 younger drivers, eight were in the low activity group and nine were in the high activity group. Among the 18 older drivers, there were nine in each of the low and high activity groups. A brief description of demographics of the low and high activity groups within the younger and older cohorts were presented in Table 3.

Table 3

Participant demographics, mean number of occurrences, mean duration of each activity occurrence, and the total duration of all activities of younger and older drivers with low or high levels of engagement in non-driving-related activities.

		Younger		Older	
		Low Activity	High Activity	Low Activity	High Activity
Demographics					
	Mean age	18.8	20.9	69.9	70.9
	% of men	75%	56%	67%	56%
Mean # of Occurrences (counts)					
	Reading	0.0	0.0	0.0	0.0
	Reaching	0.0	0.7	0.1	0.6
	Grooming	5.5	6.8	2.1	6.7
	Electronic Device [a, g, a×g]	2.3	10.0	0.0	0.7
	Horseplay	0.0	0.0	0.0	0.0
	Talking to others [a, g, a×g]	0.5	0.8	2.2	7.4
	Talking to self	0.5	2.7	0.7	0.4
	Music	0.0	0.0	0.1	0.0
	Eyes off road	17.9	30.1	13.7	14.2
Mean Duration Per Occurrence (seconds)					
	Reading	0.0	0.0	0.0	0.0
	Reaching	0.0	0.1	0.9	2.0
	Grooming	6.1	5.5	1.5	8.6
	Electronic Device [a, g, a×g]	12.7	47.6	0.0	10.9
	Horseplay	1.4	0.0	0.0	0.0
	Talking to others [a, g, a×g]	1.0	0.4	6.6	24.5
	Talking to self	2.7	7.1	0.3	7.2
	Music	0.0	0.0	5.1	0.0
	Eyes off road	6.8	5.4	8.0	5.9
Total Duration of all activities (seconds) [g]		99.5	554.2	27.4	336.0

Note:
a – significant age difference, g – significant activity group difference, a×g – significant age by group interaction

The frequency and total duration of each non-driving-related activity (i.e., reading, grooming, electronic device use, communication with others, communication with self, horseplay, and listening to music) were analyzed using MANOVAs with age (younger, older) and activity level (low activity, high activity) being the fixed factors. Mean occurrences of non-driving-related activities, mean duration per occurrence, and the total duration of all activities of younger and older drivers with low or high levels of activity engagement were listed in Table 2. In general, younger and older drivers did not differ on the number of occurrences of all activities combined, $F(1,31) = 2.60$, $p = .12$. However, younger drivers on average spent a longer total amount of time on the non-driving-related activities, $F(1,31) = 12.56$, $p = .001$.

Younger and older drivers were also engaged in vastly different activities. Younger drivers showed more occurrences of using an electronic device, $F(1,31) = 79.96$, $p < .001$, and a longer duration for each use of the device, $F(1,31) = 19.94$, $p < .001$. Older drivers initiated more conversations with the experimenter (most not related to the instruction of the driving task), $F(1,31) = 12.29$, $p = .001$, and spent more time in each conversation, $F(1,31) = 36.05$, $p < .001$. Younger drivers had more occurrences of eyes being off the road, $F(1,31) = 5.19$, $p = .030$, although the mean duration of each glance off the road did not differ between younger and older drivers, $F(1,31) = .15$, $p = .704$.

Performance on Vehicle Control during Takeover

Performance on vehicle control was analyzed based driving data collected in the takeover zone. Data indicating vehicle control performance includes speed, lateral lane position, brake input, throttle input, steering wheel angle, and notification response time.

These measures were selected based on their use in previous studies (Merat et al., 2014) as well as being identified as being relevant to assessing driving performance (SAE International, 2015). Analyses of speed, lateral lane position, brake input, throttle input and steering wheel angle were based on data recorded by the driving simulator. Notification response time was defined as the amount of time from the presentation of an auditory takeover notification to the first relevant action of the driver (i.e., hands returned to the steering wheel or feet returned to a pedal, whichever came first), and was based on the time data coded from the video recordings of participants' driving. Multiple mixed between-within repeated-measures ANOVAs were used to analyze the effect of age, level of activity engagement and takeover notification interval on these measures of vehicle control performance. The within-subject factor was the takeover notification interval (7.5 s, 4.5 s). Between-subject factors include age (younger, older) and level of engagement in non-driving-related activities (low activity, high activity). In the following section, the results on each outcome measure of driving performance are presented, including speed, lane position, brake input, throttle input, steering wheel angle and notification response time. All statistics from the analysis of variance can be found in an overview, Table 4.

Speed. The average speed (measured in km/h) was analyzed in the takeover zone, which expanded a length of 121.9 meters (400 feet) starting from the point of transfer of control from the vehicle to the driver. The average speed was significantly higher for the longer warning interval (7.5 s interval – 60.31, 4.5 s interval – 56.04), $F(1,31) = 15.33$, $p < .001$ (Figure 4a), suggesting that driver takeover of control from the vehicle is more seamless

with a longer time to prepare (i.e., less change in speed on average as compared to the speed during automated driving). Younger drivers also drove at a higher speed after the takeover (younger – 64.97, older – 51.36), $F(1,31) = 39.20$, $p < .001$. The average speed differed significantly between the low and high activity groups within each age group, and the patterns were different, $F(1,31) = 5.92$, $p = .021$. Among younger drivers, the high activity group drove faster than the low activity group (younger: low activity – 61.89, high activity – 68.06), $F(1,15) = 5.26$, $p = .037$; while among older drivers, the difference on average speed between the high activity group and the low activity group did not reach significance (older: low activity – 53.57, high activity – 49.16), $F (1,16) = 1.71$, $p = .210$. None of the other two-way or three-way interactions were significant.

Lane Position. The driver's lane position was analyzed based on the physical position of the vehicle on the road. The standard deviation was then derived to determine the consistency at which drivers maintained their position on the road. The lane position was more deviated from the road centerline with the longer takeover notification interval (Figure 4b; 7.5 s interval – 1.23, 4.5 s interval – 1.01), $F(1,31) = 19.05$, $p < .001$. Older drivers
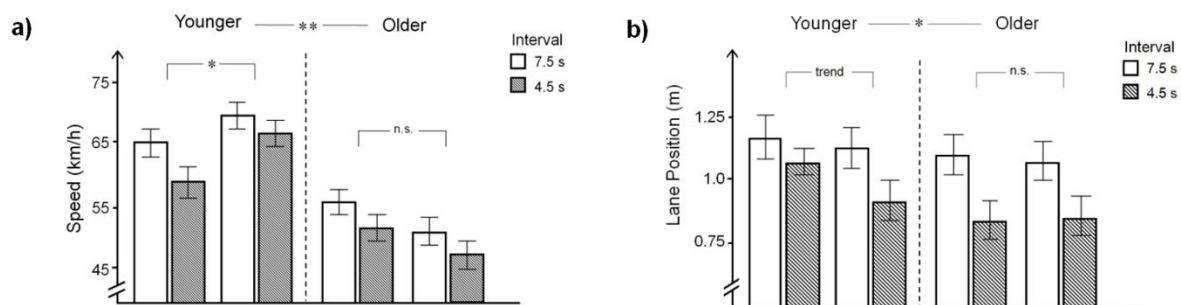

Figure 4. a) Average speed in the takeover zone of low and high activity groups within the younger and older driver cohorts. b) Lane position in the takeover zone of low and high activity groups within the younger and older driver cohorts. Error bars represent ± 1 standard error of the mean. *p < .05; **p < .001; n.s. stands for non-significance; and trend stands for .05 ≤ p ≤ .10.

deviated less from the road centerline (younger – 1.17, older – 1.06), $F(1,31) = 4.82$, p =
.036. Among older drivers, there was no difference on lane deviation between the low
activity and the high activity groups (older: low activity – 1.06, high activity – 1.05), $F(1,16)$
= .001, p = .979. Among younger drivers, there was a trend of low activity group showing
more deviation (younger: low activity – 1.23, high activity – 1.12), $F(1,15) = 3.29$, p = .090.
None of the other two-way or three-way interactions were significant.

Brake Input. Participants' brake inputs in the takeover zone were analyzed, and
reported in meters per second squared, with negative values indicating the distance lost due
to brake inputs. Brake input was significantly less intense for the longer notification interval
(7.5 s interval – -2.13, 4.5 s interval – -2.76), $F(1,31) = 10.04$, p = .003. This benefit of less
intense braking from the longer notification interval was found much more sizable in the low
activity groups than the high activity groups (low activity: 7.5 s interval – -1.73, 4.5 s interval
– -2.83; high activity: 7.5 s interval – -2.53, 4.5 s interval – -2.70), $F(1,31) = 5.45$, p = .026,
in both younger and older drivers (as indicated by a lack of age × interval × activity group
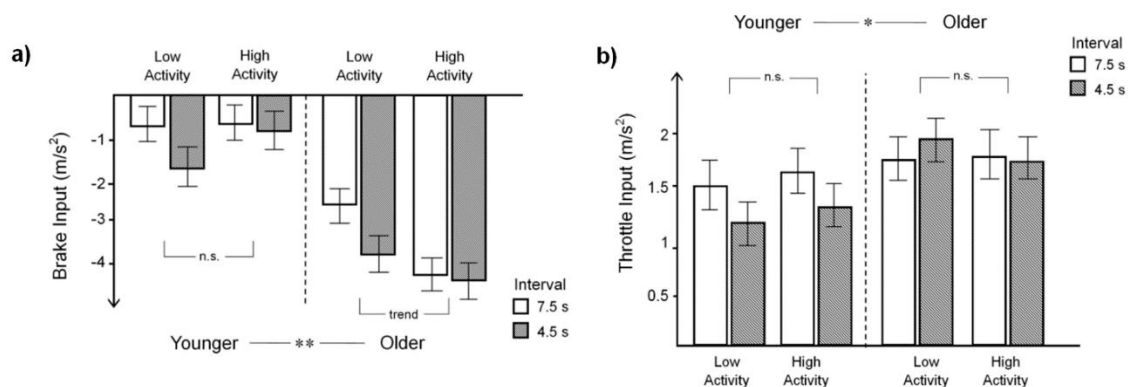

Figure 5. a) Average brake input in the takeover zone of low and high activity groups within the
younger and older driver cohorts. b) Average throttle input in the takeover zone of low and high
activity groups within the younger and older driver cohorts. Error bars represent ± 1 standard
error of the mean. *p < .05; n.s. stands for non-significance, and trend stands for .05 ≤ p ≤ .10.

interaction), F(1,31) = .03, p = .860. Older drivers placed significantly more pressure on the

brake pedal (younger – -1.01, older – -3.89), F(1,31) = 55.89, p < .001. The pattern of how

the low activity group compared to the high activity group on brake input differ between the

two age groups, F(1,31) = 4.30, p = .047. Among younger drivers, there was no difference

between the low activity group and the high activity group (younger: low activity – -1.24,

high activity – -0.77), F(1,15) = 1.39, p = .258. However, among older drivers, there was a

trend of the high activity group had harder brakes (older: low activity – -3.32, high activity –

-4.46), F(1,16) = 3.05, p = .100. None of the other interactions were significant.

Throttle Input. Different from the previous measures, there was no difference

between the long and short notification intervals on throttle input (7.5 s interval – 1.64, 4.5 s

interval – 1.51), F(1,31) = 1.03, p =.26. Older drivers placed a significantly higher pressure

on the throttle (younger – 1.36, older – 1.79), F(1,31) = 6.22, p = .018. In both the younger
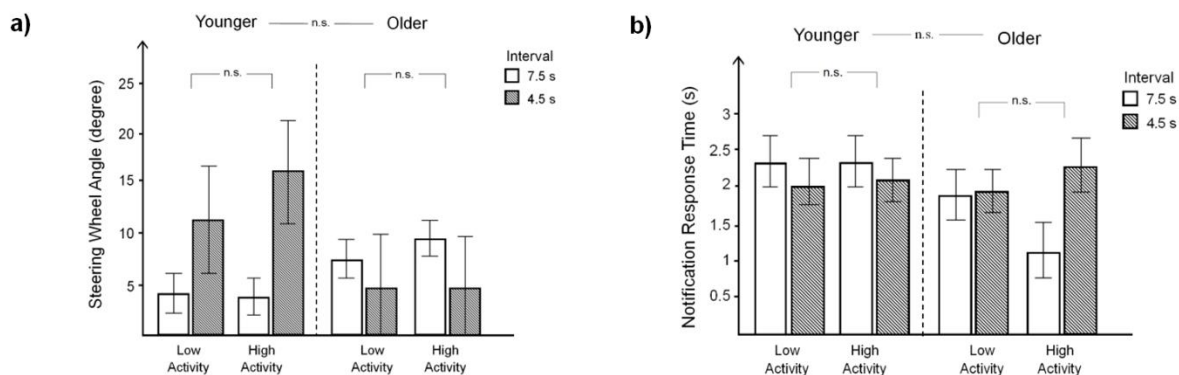

Figure 6. a) Average steering wheel angle in the takeover zone of low and high activity groups within the younger and older driver cohorts. b) Average notification response time in the takeover zone of low and high activity groups within the younger and older driver cohorts. Error bars represent ± 1 standard error of the mean. n.s. stands for non-significance.

and older cohorts, the low and high activity groups had non-differential throttle inputs. No interaction was found significant.

Steering Wheel Angle. The steering wheel angle represents the standard deviation in degree from the center position of the steering wheel. There was no difference between warning intervals (7.5s – 6.52, 4.5s – 9.52), $F(1,31) = 1.16$, $p = .291$, or between age groups (younger – 9.18, older – 6.86), $F(1,31) = .71$, $p = .407$.

Notification response time. Notification response time was calculated as the amount of time from the presentation of a takeover notification to the first relevant action of the driver. Relevant actions included hands returned to the steering wheel, feet returned to a pedal, whichever came first. Notification response time was measured in second and was based on the time data coded from the video recordings of simulated driving. There were two older participants who had either their hands on the wheel and feet on the pedals throughout the automated zone, or took relevant actions before the takeover notification for all takeovers. Therefore, no data on notification response time could be calculated for these two participants. As a result, the analysis on notification response time included data from 17 younger participants and 16 older participants. In general, there was no effect of interval (7.5 s – 1.91, 4.5 s – 2.07), $F(1,29) = 1.03$, $p = .318$, age (younger – 2.18, older – 1.80), $F(1,29) = 1.74$, $p = .197$, or activity group (low activity – 2.03, high activity – 1.95), $F(1,29) = .07$, $p = .793$. However, there was a significant interval × age interaction, $F(1,29) = 7.38$, $= .011$, and a trend of interaction between interval and activity group, $F(1,29) = 3.20$, $p = .084$. Among the younger drivers, there was no effect of interval (7.5 s – 2.32, 4.5 s – 2.05), $F(1,15) = 1.15$,

Table 4

Analysis of Variance for Driving Performance

		df (error)	F	p	Partial η²
Speed	Interval	1 , 31	15.33	< .001	.33
	Age	1 , 31	39.20	< .001	.99
	Engagement	1 , 31	.17	.687	.01
	Interval x Age	1 , 31	.10	.751	.003
	Interval x Engagement	1 , 31	.89	.352	.03
	Age x Engagement	1 , 31	5.92	.021	.16
	Interval x Engagement x Age	1 , 31	.38	.543	.01
Lane Position	Interval	1 , 31	19.05	< .001	.38
	Age	1 , 31	4.82	.036	.14
	Engagement	1 , 31	1.12	.298	.04
	Interval x Age	1 , 31	1.05	.314	.03
	Interval x Engagement	1 , 31	.11	.747	.003
	Age x Engagement	1 , 31	1.03	.318	.03
	Interval x Engagement x Age	1 , 31	.78	.383	.03
Brake Input	Interval	1 , 31	10.04	.003	.25
	Age	1 , 31	55.89	< .001	.64
	Engagement	1 , 31	.75	.395	.02
	Interval x Age	1 , 31	.01	.915	.000
	Interval x Engagement	1 , 31	5.45	.026	.15
	Age x Engagement	1 , 31	4.29	.047	.12
	Interval x Engagement x Age	1 , 31	.03	.860	.001
Throttle Input	Interval	1 , 31	1.29	.263	.04
	Age	1 , 31	6.22	.018	.17
	Engagement	1 , 31	.03	.858	.001
	Interval x Age	1 , 31	2.67	.112	08
	Interval x Engagement	1 , 31	.15	.698	.005
	Age x Engagement	1 , 31	.39	.536	.01
	Interval x Engagement x Age	1 , 31	.19	.669	.006
Steering Wheel Angle	Interval	1 , 31	1.16	.291	.04
	Age	1 , 31	.71	.407	.02
	Engagement	1 , 31	.37	.546	.01
	Interval x Age	1 , 31	6.02	.020	.16
	Interval x Engagement	1 , 31	.07	.799	.002
	Age x Engagement	1 , 31	.05	.825	.002
	Interval x Engagement x Age	1 , 31	.41	.529	.01
Notification Response Time	Interval	1 , 29	1.03	.318	.03
	Age	1 , 29	1.74	.197	.06
	Engagement	1 , 29	.07	.793	.002
	Interval x Age	1 , 29	7.38	.011	.20
	Interval x Engagement	1 , 29	3.20	.084	.09
	Age x Engagement	1 , 29	.15	.700	.01
	Interval x Engagement x Age	1 , 29	2.73	.109	.09

p = .301, or interaction between interval and group (low activity: 7.5 s – 2.31, 4.5 s –

2.02; high activity: 7.5 s – 2.33, 4.5 s – 2.08), F(1,15) = .007, p = .932. In contrast, among the

older drivers, the longer notification interval was associated with a shorter response time (7.5

s – 1.50, 4.5 s – 2.09), F(1,14) = 10.00, p = .007. There was also a significant interaction

between interval and group among the older drivers (low activity: 7.5 s – 1.87, 4.5 s – 1.92;

high activity: 7.5 s – 1.14, 4.5 s – 2.27), suggesting the longer notification interval

particularly benefited older drivers who were more engaged in non-driving-related activities.

Opinions Concerning Limited Self-Driving Vehicle Automation Survey

Survey data was analyzed with multiple mixed between-within repeated-measures

ANOVA, with session (pre-drive survey, post-drive survey) as the within-subject factor, and

age (younger, older) as the between-subject factor. Among the surveyed items, significant

age difference were found on usability concerns, with older drivers being more concerned

with potential usability issues of autonomous vehicle technology (younger – 1.53, older –

2.25; higher score meaning greater concern), F(1,33) = 9.08, p = .005. In addition, younger

drivers also reported potentially more time playing game, F(1,33) = 7.07, p = .012 than older

drivers when riding in a limited self-driving vehicle. In general, after the simulated level 3

vehicle automated driving, participants thought that there would more likely be less traffic

congestion, F(1,33) = 5.93, p = .020, and better fuel economy, F(1,33) = 4.93, p =.033. After

the simulated limited self-driving driving, participants had more concern about data privacy,

F(1,33) = 6.11, p = .019 and system performance in poor weather, F(1,33) = 8.86, p = .005.

There were also a few significant interactions between age and survey. Level 3 concern,

F(1,33) = 5.82, p = .022, reduced travel time, F(1,33) = 7.68, p = .009, and reduced insurance liability, F(1,33) = 4.45, p = .043.

GENERAL DISCUSSION

This study found that while age and takeover notification had significant impacts on driver takeover, the level of activity engagement did not, with the exception of a trend of older drivers who were highly engaged in non-driving-related tasks braking harder at the takeover. Additionally, older drivers had a higher concern with the usability of the higher level of vehicle automation following the simulated experience. In the following paragraphs, I discuss particular findings and their relation to my hypotheses.

The results indicate that both younger and older drivers tend to engage in non-driving-related activities during the automated portion of driving. However, each age group demonstrated distinct preferences on what activities to engage in. Younger drivers frequently used their electronic devices, much more than did older drivers. In contrast, older drivers were more inclined to converse with another individual. This observed difference between younger and older drivers may reflect a potential age difference in non-driving-related activity preference. It is also possible that this observed age difference in activity choice may be partially attributed to the availability of personal technology to younger and older adults. Compared to younger adults, the proportion of older adults carrying advanced personal technology such as smart phones is much smaller. Even when an older adult does use a smart phone, it is much less likely that the phone is filled with most up-to-date apps for social networking and entertainment, thus it is less fun to use. This differential availability of

personal technology to the two age groups could extend its effect to drivers' choices of non-driving-related activities in a real vehicle with conditional automation. Therefore, it is important to consider age differences in activity choice in addition to the relatively well-studied age differences in cognitive capabilities, when comparing younger and older drivers in their use of automated vehicle technology.

Interestingly, the study found that some old adults were highly involved in non-driving-related activities. The older drivers in the high activity engagement group spent an average of 336.0 s (5.5 minutes out of about 20 minutes of automated driving) on non-driving-related activities, more than three times the amount of the younger low activity group (98.5 s). In addition, the total number of occurrences of all non-driving-related activities was also comparable between younger and older drivers. Given that engagement in non-driving-related activities have been suggested to help maintain a proper alertness level in drivers when the driving demand is low (Neubauer et al., 2012; Miller et al., 2015), the younger and older drivers – particularly those in the high activity groups – in the study may be utilizing the non-driving-related activities to combat boredom and drowsiness when the vehicle was driving itself. Another possible contributor to this finding is the differences between simulated and real driving. Given the driving environment in the simulation is much simpler than what we typically encounter on daily routes, the older participants may be much more relaxed than in a real automated vehicle on road, and thus was more likely to engage in the non-driving-related activities.

Perhaps one of the most important investigations in the study is on the effect of voluntary engagement in non-driving-related activities on driver takeover performance. Among younger drivers, the high activity group drove at a higher speed after a takeover. This result may be viewed as an indication of more smooth transition of control in the high activity group (8 out of 9 younger drivers in the high activity group compared to 3 out of 8 in the low activity group maintained an average speed of within ±10% of the automated driving speed). Or, it could also possibly reflect a connection between this group's particular individual characteristics and driving behavior. Sensation seeking has been associated with higher driving speed (Jonah et al., 2001) and great involvement in non-driving-related tasks (Feng et al., 2014). The current study did not directly measure the construct of sensation seeking, thus further research is necessary to distinguish the two speculated causes. Compared to older drivers in the low activity group, the high activity group of older drivers had a comparable speed, standard deviation of lane position and notification reaction time, but potentially harsher braking (p = .10). Given significance was not obtained, but just a trend, this result on brake input should be interpreted with caution. It is possible that older drivers who engage more in non-driving-related activities during automated driving could show some degree of impairment on takeover performance (e.g., harsher braking response). However, as the sample size was small and the same effect was not found on other vehicle control measures, further examination is necessary. The finding on notification response time was consistent to Zeeb et al. (2016), that drivers could return their hands to the steering wheel equally quickly no matter whether they were engaged in a secondary activity or not.

The study allowed drivers to freely decide whether and when to engage in their chosen non-driving-related activities during automated driving. The younger and older drivers did exert a wide range of non-driving-related activities. However, being engaged in a greater amount of activity did not seem to have significant impacts on driver performance during takeover. Considering the nature at which drivers were allowed to choose their activity, or lack there of, I provided a general hypothesis that engagement in more voluntary activity would impact drivers' performance. Little difference was found except a trend of harsher braking and a greater preference of the longer notification interval (in terms of notification response time) among high activity older.

In the analyses of age differences in the performance on takeover, I found that older drivers in general drove more slowly with a smaller deviation from the road centerline after a takeover. Consistent with findings in other studies (e.g, Miller et al., 2016; Nishida, 1999), this could be an indication that older drivers tended to exercise more caution in manual driving. Older drivers also braked and accelerated harder in the study, as indicated by significantly greater impacts on vehicle dynamics that older adults made through brake and throttle inputs. Considering significant decreases in the speed of one vehicle in a traffic flow could cause backup of traffic thus increased congestion, which is typically defined as the *shockwave* effect (May, 1990), it is important to be prepared for the possible effects from takeovers on traffic efficiency and examine potential mitigation strategies for drivers who experience significant speed reduction during a takeover. These results lend much support to my initial hypothesis that older drivers would perform worse, with slower speeds likely due

to the higher brake input indicating drivers were unprepared for the takeover, however not all can be deemed poor performance and therefore further investigation is required. Additionally, driver performance was analyzed across the driving sessions, and it was hypothesized that drivers would improve with experience. Contrary to preliminary findings, this was not seen in either younger, or older drivers. However, considering the small amount of time between the first and last experimental drive, improvement could be seen with more training and experience with the vehicle technology.

The longer takeover notification interval (7.5s) was generally preferred over the shorter one (4.5s) by both the younger and older drivers. When an auditory notification was given 7.5 s before the takeover, drivers had softer brakes thus less speed change, indicating a more smooth transition of vehicle control. Additionally, older drivers, but not younger drivers, responded faster following the notifications of the longer interval than those of the shorter interval. These results support the initial hypothesis that a longer warning interval would lead to better performance, however, in general, there was no additional evidence from other vehicle control measures suggesting that older drivers benefit more from a longer takeover notification interval. Similar to what's been proposed in other studies showing better than expected performance of older drivers in highly automated driving (e.g., Miller et al., 2016; Körber et al., 2016), it may also be due to the relatively high cognitive functioning of healthy older research participants, their extensive expertise in driving, and compensatory behaviors such as driving more slowly and keeping a longer headway distance.

The results obtained from the survey, administered both before and after the experimental driving sessions, are considered preliminary given the small sample size. In general, there was no connection between the survey results and driving performance, in particular when comparing between the older and younger drivers. Minimal results were seen from the survey, however the most notable being concern for usability. Older drivers reported a higher concern for usability of the vehicle technology following their experience in the simulated drive. When comparing these results, however few, to the initial administration of the survey (Schoettle & Sivak, 2014) it's important to note that this concern for usability was not seen in their reported results. This is likely due to the fact that the participants in this study were informed of the multiple levels of vehicle automation, and encouraged to answer according to limited self-driving, instead of completely self-driving as with Schoettle & Sivak. These findings do not directly support either of our hypotheses, however give rise to the consideration that developers and vehicle designers should make with the inevitable introduction of these vehicles to the public. Training, and much more information, should be provided to drivers prior to their engagement and operation of these limited self-driving vehicles.

While the study informs about the understanding of how older drivers interact with highly automated vehicle technology, there are several limitations of the current study that I would like to discuss. First, the examination of how engagement in non-driving-related activities impacts takeover performance is correlational. Further experimentation and analyses are needed to contrast takeover performance when a driver engages in secondary

activities to that performance when the same driver does not engage in any secondary

activity. Second, due to technical restrictions, it was not possible to simulate lifelike driving

with conditional automation. The scenarios were quite simple and the takeovers were not

very challenging. The performance measures used in this study were also basic. More

advanced measures such as time-to-collision in driving scenarios containing driving hazards

are necessary in future investigations of the effect of voluntary engagement in non-driving-

related activities. Third, the notification to takeover was only presented auditorily in the

present study. Given a multimodal display (e.g., auditory message plus a visual presentation)

could be more effective than a unimodal display (Cohen, Cohen, Mendat, & Wogalter, 2006)

in notifying the driver about the upcoming takeover, the results could be further validated

with improved notification interface. Fourth, healthy older participants recruited to

behavioral studies are in general with more years of education, higher social economic status,

better cognitive functioning than the general older population. This may lead to difficulty of

generalization of the findings to the overall older population. However, the group of older

participants typically drawn to behavioral studies is also the subgroup of older adults who are

most likely to afford the advanced vehicle technology, and they may indeed be the early

adopters of the technology among the general older population. Fifth, the present study was

based on a relatively small sample size (n = 35). Some trends (e.g., older drivers engaged in a

high level of non-driving-related activity tended to brake more harshly than those showed a

low level of activity) were identified, which should be further examined in experiments with

larger sample sizes. The results provided a basis for estimation of required sample size of future studies.

Future research should seek to validate current findings in a higher fidelity driving simulator equipped with more lifelike control functions in an automated vehicle and the capability to simulate more realistic automated driving situations with a larger sample size. Considering the recent advancements in research surrounding these technologies (Delphi Automotive, 2015; Tesla Motor Company, 2015) the inclusion of driver alertness and engagement in non-driving-related activities is feasible, and a likely next step. In addition, age differences in driving are phenomenological rather than essential. To understand the nature of age differences in automated driving, research needs to look into how various individual characteristics such as cognitive abilities (e.g., Körber et al., 2015), personality, and experience with technology lead to observed age differences in driving. Such knowledge would largely enhance the understanding of driving behavior at the individual level, as significant individual variation exist within each age group on almost any cognitive, psychological, or social construct.

The findings imply several considerations on the design of in-vehicle interface for automated driving technology. First, two intervals of auditory notification were used, 4.5 s and 7.5, both being shorter than the 10 s interval used for visual notifications in a previous study (Merat et al., 2014). This is consistent with the notion that auditory notifications are more commonly used as warning signals and emergency alarms (Walker & Kramer, 2006) interval design. Both the younger and older participants performed takeover well under the

two notification conditions, although there was a general preference of the longer interface. The results suggest possible use of shorter than previously considered intervals, when the notification could be presented auditorily. Second, a significant portion of older drivers tend to engaged heavily in non-driving-related activities. Given engagement in these activities could help a driver to maintain a proper level of alertness when the driving task was not demanding (Neubauer et al., 2012; Miller et al., 2015), the increased activity engagement in older drivers may be an adaptive behavior that could be beneficial. The study also found significant age difference in activity preference (e.g., younger drivers prefer to use an electronic device, while older drivers tend to engage in conversations). This implies the importance of providing safe options for non-driving-related activities in the vehicle during automated driving, if engagement in these activities plays an essential role in the maintenance of driver alertness. Therefore, further investigations on the variety of activities that younger and older drivers tend to engage in and determining the safety implications are critical for future development of in-vehicle interface for high automated vehicles. Third, the average durations of eyes-off-road per activity occurrence among the younger and older drivers was quite lengthy in both the low and high activity groups (5-8 seconds; Table 2). This has important implications of designing in-vehicle displays that communicates information visually. During automated driving, presentation of visual information may need to be accompanied by notifications using other sensory modalities (e.g., auditory, tactile) which could alert the driver to look at the visual display.

CONCLUSION

While the idea of highly automated vehicle technology is exciting to many, including older drivers, there are many critical human factors issues that need to be addressed. For example, vehicle interface design, warning (both visual and auditory) design, and training. In this study, I observed how younger and older drivers voluntarily engaged in non-driving-related activities during the automated portion of simulated driving using video recording and a behavioral coding method. The study examined the effect of age, level of activity engagement, and notification-of-takeover interval on driving performance during the takeover of vehicle control. Significant age differences in the type of activities that younger and older drivers engaged in were found. I also observed effects of age, level of activity-engagement, and takeover notification interval. Older drivers benefited more than younger drivers from the longer notification, particularly the group who engaged more in the non-driving-related activities. Future research is needed to explore the case of driver voluntary engagement in non-driving-related activities, which may reveal differential findings compared to mandatory engagement in these activities.

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APPENDICES

Appendix A

Survey on limited self-driving vehicle automation adapted from Opinions Concerning
Autonomous and Self-Driving Vehicles (Schoettle & Sivak, 2014)

We are conducting a survey of opinions about autonomous and self-driving vehicles.

A general explanation of what is meant by autonomous and self-driving vehicles will be
shown on the next page. Please take a moment to read that description carefully before
continuing with the survey.

Autonomous vehicles are those in which at least some aspects of a safety-critical control
(such as steering, throttle, or braking) operate without direct driver input.
Vehicles that provide safety warnings to drivers (for example, a forward-crash warning)
but do not take control of the vehicle are not considered autonomous.

Autonomous vehicles may use on-board sensors, cameras, GPS, and telecommunications
to obtain information in order to make decisions regarding safety-critical situations and act
appropriately by taking control of the vehicle at some level. Examples of autonomous-
vehicle technologies range from those that take care of basic functions such as cruise
control, to completely self-driving vehicles with no human driver required.

Q1) Had you ever heard of autonomous and/or self-driving vehicles before participating
in this survey?

    Yes
    No

Q2) What is your general opinion regarding autonomous and self-driving vehicles?
*Even if you had never heard of autonomous or self-driving vehicles before participating
in this survey, please give us your opinion based on the description you just read.*

    Very positive
    Somewhat positive
    Neutral
    Somewhat negative
    Very negative

There are several different levels of autonomous-vehicle technology. Some of these technologies already exist now, while others are expected to become available in the future. Descriptions of each level of autonomous vehicle technology are shown below.
Please take a moment to read each description carefully before continuing with the survey.

Current technology:
Level 0. No autonomous-vehicle technology.

Level 1. The vehicle controls one or more safety-critical functions, but they operate

independently. The driver still maintains overall control.

Level 2. This level combines two or more technologies from Level 1, but they operate in coordination with each other. The driver still maintains overall control.

Future technology:
Level 3. This level provides limited self-driving technology. The driver will be able to

hand control of all safety-critical functions to the vehicle, and only occasional control by

the driver will be required.

Level 4. Completely self-driving vehicle. The vehicle will control all safety-critical functions for the entire trip.

Q3) Which of the following autonomous-vehicle technologies, if any, do you have on the vehicle(s) that you own or lease?

Please select one response only. If you have more than one vehicle with this technology, please select the most advanced level installed on your vehicles.

☐ I do not currently own or lease a vehicle

☐ Level 0: No automation. The driver is in complete and sole control of the primary vehicle controls (brake, steering, and throttle) at all times, and is solely responsible for monitoring the roadway and for safe operation of the vehicle. Vehicles that have certain driver support or convenience systems but do not have control over steering, braking, or throttle would still be considered Level 0 vehicles. Examples include systems that provide only warnings (forward collision warning, lane departure warning, blind spot monitoring), as well as systems providing automated secondary controls such as wipers, headlights, (*U.S.: turn signals, U.K./Australia: indicators*), hazard lights, etc.

☐ Level 1: Automation at this level involves one or more primary vehicle controls (brake, steering, or throttle); if multiple controls are automated, they operate independently from each other. The driver has overall control, and is solely responsible for safe operation, but can choose to hand over limited control to the vehicle (such as cruise control); or the vehicle can automatically control a function (such as electronic stability control); or the vehicle can provide added control to aid the driver in certain situations (such as dynamic brake support in emergencies). The vehicle may assist the driver in operating one of the controls—steering, braking, or throttle—but each function is controlled independently from the others. Other examples of Level 1 systems include automatic braking and automatic lane keeping.

☐ Level 2: This level involves automation of at least two primary vehicle controls (brake, steering, and/or throttle) designed to work together to relieve the driver of control of those functions. Vehicles at this level of automation can share control with the driver in certain limited driving situations. The driver is still responsible for monitoring the roadway and safe operation, and is expected to be available for control at all times and on short notice. The system can relinquish control with no advance warning and the driver must be ready to control the vehicle safely. An example of a Level 2 system is adaptive cruise control in combination with automatic lane keeping. Automatic parking systems are also considered Level 2.

☐ I do not know if my vehicle has any of these technologies

Q4) Level 3 vehicles are expected to provide limited self-driving automation. Vehicles at this level enable the driver to hand over control of all safety-critical functions under certain traffic conditions, and to rely on the vehicle to monitor for changes that require switching back to driver control. The driver will be expected to be available for occasional control, but with sufficiently comfortable transition time. An example would be a self-driving car that can determine when the system is no longer able to support automation, such as in a construction area, and then signals the driver to take control of the vehicle with an appropriate amount of time to safely react. The major difference between Level 2 and Level 3 is that at Level 3, the vehicle is designed so that the driver is not expected to constantly monitor the roadway while driving.

How concerned would you be about driving or riding in a vehicle with this level of self-driving technology?

    Very concerned
    Moderately concerned
    Slightly concerned
    Not at all concerned

Q5) Level 4 vehicles are expected to provide complete self-driving automation. The vehicle will be designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. The "driver" will provide destination or navigation input, but will not be expected to be available for control at any time during the trip. This includes both occupied and unoccupied vehicles. By design, safe operation rests solely with the automated vehicle system. (*Question 5 continues on to the next page*)

How concerned would you be about riding in a vehicle with this level of self-driving technology?

       Very concerned
       Moderately concerned
       Slightly concerned
       Not at all concerned

Q6) How likely do you think it is that the following benefits will occur when using **limited self-driving vehicles (Level 3)**?

Please select one response per row.

	Very likely	Somewhat likely	Somewhat unlikely	Very unlikely
a. Fewer crashes	☐	☐	☐	☐
b. Reduced severity of crashes	☐	☐	☐	☐
c. Improved emergency response to crashes	☐	☐	☐	☐
d. Less traffic congestion	☐	☐	☐	☐
e. Shorter travel time	☐	☐	☐	☐
f. Lower vehicle emissions	☐	☐	☐	☐
g. Better fuel economy	☐	☐	☐	☐
h. Lower insurance rates	☐	☐	☐	☐

Q7) How concerned are you about the following issues related to **limited self-driving vehicles (Level 3)**?

Please select one response per row.

	Very Concerned	Moderately Concerned	Slightly Concerned	Not at all Concerned

		Very Concerned	Moderately Concerned	Slightly Concerned	Not at all Concerned
a.	Safety consequences of equipment failure or system failure	☐	☐	☐	☐
b.	Legal liability for "drivers"/owners	☐	☐	☐	☐
c.	System security (from hackers)	☐	☐	☐	☐
d.	Vehicle security (from hackers)	☐	☐	☐	☐
e.	Data privacy (location and destination tracking)	☐	☐	☐	☐
f.	Interacting with non-self-driving vehicles	☐	☐	☐	☐
g.	Interacting with pedestrians and bicyclists	☐	☐	☐	☐
h.	Learning to use self-driving vehicles	☐	☐	☐	☐
i.	System performance in poor weather	☐	☐	☐	☐
j.	Self-driving vehicles getting confused by unexpected situations	☐	☐	☐	☐
k.	Self-driving vehicles not driving as well as human drivers in general	☐	☐	☐	☐

Q8) How concerned are you about the following possible scenarios with **limited self-driving vehicles (Level 3)**?

Please select one response per row.

		Very Concerned	Moderately Concerned	Slightly Concerned	Not at all Concerned
a.	Riding in a vehicle with no driver controls available (no steering wheel, no brake pedal, and no gas pedal/accelerator)	☐	☐	☐	☐
b.	Self-driving vehicles moving by themselves from one location to another while unoccupied	☐	☐	☐	☐
c.	Commercial vehicles such as heavy trucks or semi-trailer trucks that are completely self-driving	☐	☐	☐	☐
d.	Public transportation such as buses that are completely self-driving	☐	☐	☐	☐
e.	Taxis that are completely self-driving	☐	☐	☐	☐

Q9) How interested would you be in having a **limited self-driving vehicle (Level 3)** as the vehicle you own or lease?

Very interested

Moderately interested
Slightly interested
Not at all interested

Q10) If you were to ride in a **limited self-driving vehicle (Level 3)**, what do you think you would use the extra time doing instead of driving?

Please select one response only.

Text or talk with friends/family
Read
Sleep
Watch movies/TV
Play games
Work
Watch the road even though I would not be driving
I would not ride in a completely self-driving vehicle
Other (please specify): _____

Thank you for completing this survey about autonomous and self-driving vehicles!