Driver Behavior While Operating Partially Automated Systems: Tesla Autopilot Case Study

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John Shutko
Ford Motor Company

Ben Osafo-Yeboah
Ford Motor Company

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John Shutko and Benjamin Osafo-Yeboah Ford Motor Co., Ltd.

Chris Rockwell and Mark Palmer Lextant

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Abstract

Level 2 (L2) partially automated vehicle systems require the driver to continuously monitor the driving environment and be prepared to take control immediately if necessary. One of the main challenges facing developers of these systems is how to ensure that drivers understand their role and stay alert as the systems require. With little real world data, it has been difficult to understand user attitudes and behaviors toward the implementation and use of partially automated vehicles. At the time of this study, Tesla was one of the few OEMs with a partially automated vehicle feature available on the market; Autopilot. In order to understand how customers interact with a partially automated vehicle, a study was conducted to observe people driving their own Tesla vehicles while autopilot was engaged.

Sixteen Tesla owners (14 males and 2 females) between ages 25 to 60 had their vehicles instrumented with video/audio data collection systems for three consecutive days. These owners were dedicated autopilot users who used the feature daily and primarily on highways. Results from the study show that (i) participants' eye off-road glance behavior while operating a partially automated vehicle was somewhat similar to eye off-road glance behavior in radio tuning task while driving manually, though substantially more variable, (ii) eyes on/off road glance behavior had no relation to whether drivers kept their hands on the steering wheel or not, (iii) drivers exhibit a bi-modal behavior when operating a partially automated vehicle: those who mostly kept their hands on steering wheel while autopilot was active (i.e. *active drivers*) verses those who mostly kept their hands off the steering wheel while autopilot was active (i.e. *supervisors*).

Introduction

Automobiles have come a long way since they were introduced over a century ago. In the United States today, there are more than one car per licensed driver. This is a reflection of the need for individuals to drive in order to participate effectively in the modern economy, and to maintain an enriching social life [1]. While driving allows economic participation and social enrichment, it is also a leading cause of death in the United States. Over thirty thousand lives are lost each year on American roads, mostly attributed to human error [2]. Recent advances in technology has led to the development and deployment of advanced driver assistance systems (ADAS) with the goal of enhancing safe and efficient driving. While ADAS systems enhance safe driving, they also serve as building blocks for the eventual development of automated vehicles. Currently, SAE defines six levels of automated driving systems: level 0 through level 5, with level 0 having no automation, while level 5 is fully autonomous driving.

Partially automated driving systems, called Level 2 (L2) systems, are defined by SAE J3016 as automated vehicles in which the system performs the execution of steering and acceleration or deceleration of the vehicle while the human driver monitors the driving environment [3]. In other words, the driver must be alert and attentive, in order to detect and respond appropriately to events that are beyond the capabilities of the partially automated driving system. Therefore, in order for a partially automated vehicle to operate effectively, the driver must be alert at all times. However, it has been found that drivers' ability to perceive critical factors within their environment or to detect system changes or failures may be diminished relative to engaged and alert manual driving as their role shifts from active vehicle control to passive monitoring, primarily due to loss of awareness of the state and the processes of the system [4, 5].

One of the many challenges that developers of partially automated driving vehicles are grappling with currently is how to ensure that drivers understand their role and remain alert while operating a partially automated vehicle. In particular, there are concerns that drivers' willingness to engage in non-driving related tasks will be impacted while operating a partially automated vehicle due to the increased use of nomadic electronic devices, and the reduction in workload provided by these systems [6, 7]. However, little research has been done on driver attitude and behavior while operating a partially automated vehicle.

With much speculation and little experience, it has been difficult to forecast user attitudes and behaviors while using autonomous driving features. Currently Tesla is one of the few manufacturers who has a vehicle on the market with partially automated driving functionality available to the driver (i.e. autopilot). The goal of present study was to understand Tesla owners' driving behavior while autopilot is active, and to help understand what influence drivers' use of the feature. To help evaluate these goals, a naturalistic study was conducted using instrumented Tesla vehicles to collect data over a three-day period.

Methodology

Participants

Sixteen (16) drivers, between 25 to 60 years of age with autopilot version 8.0 equipped Tesla Model S vehicles were recruited from Phoenix, AZ and Columbus, OH metro areas through newspaper ads to participate in this study. Participants consisted of 14 males and 2 females, each with a valid drivers' license. Six (6) participants were considered novices (they had 4 months or less experience using autopilot), while 10 were considered experienced (they had more than 4 months experience using autopilot). Each participant had their Tesla vehicle outfitted with two discreet video/audio capture system that recorded all their drives over a 3-day period. Each participant received a $250 compensation for their participation.

Study Design

The study consisted of a 3-pronged approach of journaling, observation and interview. This approach allowed the authors to identify situations in which Tesla owners use autopilot, what they do when autopilot is enabled, and how they feel about using autopilot.

Journaling One week prior to the observation and interview, participants created a journal of how often they used autopilot, what situations prompted them to use autopilot, and how they felt about their experience with autopilot.

Observation Each participant had his/her Tesla Model S outfitted with two discreet video/audio capture systems that recorded all their drives over a 3-day period.

Interview At the end of the observational period, the experimenters conducted a one hour retrospective interview to review, discuss, and understand participants' behaviors during the use of autopilot.

Procedure

One week before the observation and interview sections, participants documented their autopilot usage. Specifically, how often they used autopilot, the situation that prompted autopilot use, and the experience they had using autopilot.

After one week of journaling, participants drove their vehicles to a research facility where technicians outfitted their vehicle with audio/video capture system. Two audio/video recording systems were discreetly installed. A forward over the shoulder camera recorded the road scene and the cluster human machine interface (HMI), while a rear facing camera recorded both the driver's face and hands. The audio/video capture system was set up such that, the driver had to press a button to start the recording on each drive. Once instrumented, participants drove their vehicles as they typically would. The video/audio recording system, recorded all their drives for the next three days. No participant reported that they forgot to activate the audio/video system on any drive.

On the third day of observation, two experimenters met each participant at a pre-arranged location, and followed the participant during one of their typical drives. During this drive, the experimenters used a remote video "beaming" system to remotely access and observe participants while they go about their typical errands. At the end of the trip, the experimenters conducted a one-hour interview with the participant. The interview included follow-up questions from the interactions observed during the remote video "beaming" session. The interview session was recorded for future analysis. The video/audio capture system was removed from participants' vehicle at the end of the third day.

Results

Qualitative Data

Autopilot Understanding and Usage Situations All participants (16 out of 16) treated the autopilot feature as a driver assistance feature, and understood that the driver was primarily responsible for the safe operation of the vehicle even when autopilot was active. Participants used autopilot in a variety of situations both on and off highways. In particular, all participants cited one or both of the following as a reason for activating autopilot.

i. When lane markings were clearly visible, because they believed autopilot could track and keep them in the lane more effectively
ii. When they were in traffic situations, because they knew from experience that autopilot could track effectively the vehicle in front of their vehicle.

System Expectations In a subjective evaluation, participants reported realistic expectations for Tesla's autopilot feature prior to purchase. No participant reported that he or she expected autopilot to drive for them without any driver monitoring. Instead, participants described autopilot as a driver assistance or backup feature. All 16 participants reported that they had completed extensive research (through forums, Tesla news updates, news articles, Tesla sales, and tech crew) on the capabilities and limitations of autopilot prior to purchase.

Initial Exposure Despite having realistic expectations prior to purchase, participants' expectations of autopilot dropped further during the first few months of ownership, as they experienced real world limitations of the feature. However, expectations improved after the initial few months of ownership as drivers learned how the system worked, and how and when it could be used. All 12 participants who had more than two months of experience with the system reported having less dissatisfaction and uncertainty in autopilot's capabilities after becoming familiar and comfortable with the system through positive driving experiences.

Effect of Autopilot Accident on Driver Behavior

The fatal crash that killed a Tesla driver while using autopilot happened three months prior to this study, therefore, participants were asked if the crash had any impact on their use or attitude towards autopilot. All 16 participants reported that they considered the accident a "wake up call" and that it made them more conservative in their expectations of autopilot. Specifically, most participants reported that they changed their driving behavior by spending less time doing non-driving related tasks, and more time monitoring the road ahead when autopilot was active. In spite of the behavior change, participants were not deterred from using autopilot and unanimously attributed the accident to misuse of the feature.

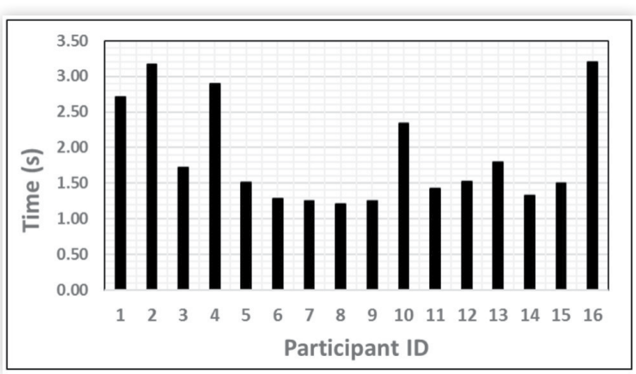
Behavior Analysis

A detailed analysis of driver behavior while autopilot is engaged, was conducted using eye glance data and driver hands-on/off steering wheel data. The following two sections provide details on eye glance and hands-on steering wheel results.

Eye Glance Analysis

Overall, a total of 2210 eyes off-road glances (glances away from road scene) were recorded while autopilot was active. Eye glance reduction was manually coded. Average duration of a single glance away from road for all participants was 1.66 s, with a standard deviation of 3.60s. Typically, glances away from the road included glances to the cluster, center console, phone, or a food item. Average single glance time away from road per participant ranged from 1.20s to 3.20s. Average single glance away from road per participant while autopilot was active is shown in Figure 1.

FIGURE 1 Average Duration of a Single Glance away from Road while Autopilot is Active



To compare driver eye glance behavior while autopilot was engaged to known driver eye glance behavior while driving manually, a frequency distribution of all eyes off-road glance durations observed while the vehicle was in autopilot mode was plotted, as shown in Figure 2.

The frequency distribution plot indicated a mean duration of a single glance away from road was 1.66 s, while the median duration of a single glance away from road was 1.06 s. The 85th and 95th percentile duration of a single glance away from road were 2.41 s and 4.14 s respectively.

These results were comparable to single glance durations observed while tuning a car radio in manual driving as reported by [8] (see Figure 3). The mean off-road single glance duration in autopilot was somewhat longer than the mean single glance in a radio tuning task while driving manually (1.66 s vs. 1.44 s, respectively). However, the variability in single glance durations is roughly 7 times greater during autopilot driving compared to driving manually and tuning a radio (standard deviation of 3.6 s vs. 0.5 s, respectively).

Similarly, the results from eye off-road glance duration from the current study is consistent with results obtained by [9], which reported a median single off-road glance durations 2.18 s and 3.61 s respectively in a scheduled versus reference conditions in dynamic simulator environment.

FIGURE 2 Driver Eyes Off-Road Glance Distribution while Autopilot is Engaged

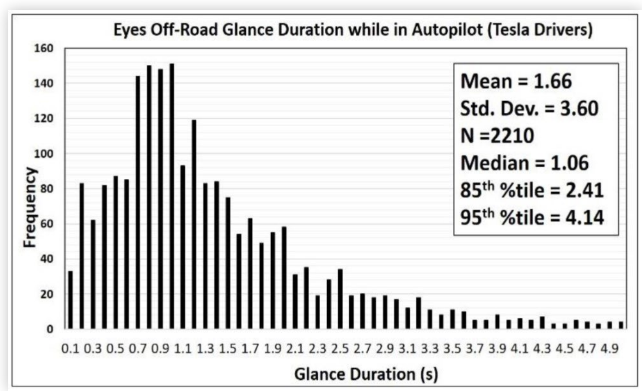
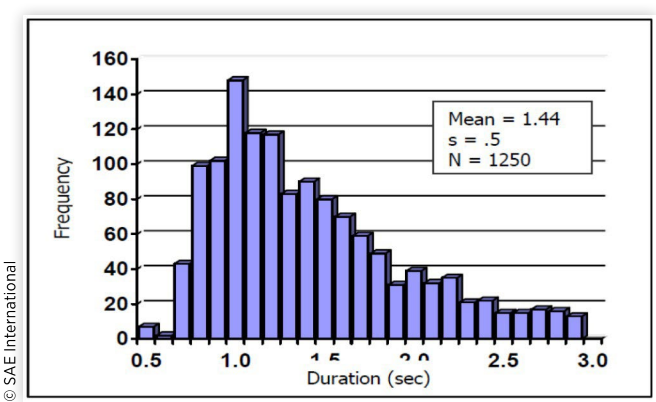


FIGURE 3 Distribution of eye glance duration when manually tuning a radio (Source Rockwell, 1988)



Further, analysis of eye glance data showed that participants kept their eyes on the road about 89% of the total time that autopilot was active. Again, this finding from the current study is consistent with results reported by [10], which found that in a car following experiment, participants had their eyes on-road 86% of the time.

Thus, contrary to the perception that drivers may disengage when operating a partially automated vehicle, results from this study showed that drivers stayed alert and generally kept their eyes on the road. The results showed that typical (average) eyes off-road duration while autopilot was engaged is consistent with eyes off-road duration while tuning a radio in manual driving, though variation was substantial in autopilot driving.

Hands-On/Off Steering Wheel

Driver hands-on/off steering wheel while autopilot was active was compared to eyes off-road behavior and experience level of the driver. Table 1 below provides a summary of driver experience, eyes on-road and hands-off steering wheel behavior while autopilot was active.

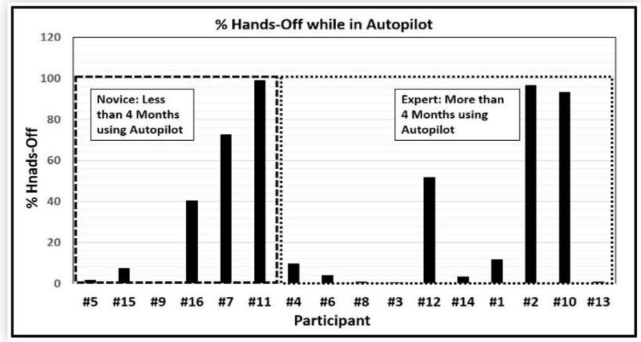
The results showed that the level of autopilot usage experience did not influence percentage eyes on/off-road or percentage hands-on/off steering wheel. Participants' level of experience and percentage hands-off steering wheel is shown in Figure 4.

In addition, the results indicated that driver hands-on-wheel behavior is bi-modal. Eleven drivers kept at least one hand on the wheel less than 50% of the time, while the remaining five drivers kept one or both hands off the wheel 50% of the time or more while Autopilot was engaged. In essence, there were broadly two types of drivers: "*active drivers*" and "*supervisor drivers*". Regardless of the length of autopilot experience, *active drivers* kept their hands on the steering wheel for most of the time while autopilot was active. On the other hand, *supervisors* kept their hands-off the steering wheel most of the time while autopilot was active. When asked, *active drivers* said they kept their hands on the steering wheel to: (i) ensure they were ready to take control when necessary, and (ii) avoid receiving hands-off warning from the system. On the contrary, *supervisors* said they kept their hands off the steering wheel because: (i) they felt comfortable and confident in the system, and (ii) they did not want to accidentally disengage autopilot. The authors believe this behavior is attributable to individual differences and acceptance of automation.

TABLE 1 Driver Experience, Eyes On-Road, and Hands-Off Steering Wheel while Autopilot is Active

Participant ID	Length of Experience	% Eyes on-Road while in Autopilot	% Hands-Off while in Autopilot
5	3 weeks	93.1	1.6
15	3 weeks	93.9	7.3
9	less than 2 month	84.3	0
16	less than 2 month	78.8	40.4
7	2-4 months	79.2	72.6
11	2-4 months	93.3	99
4	4-8 months	86.5	9.5
6	4-8 months	96.5	4
8	4-8 months	96.7	0.7
3	8m - lyr	97.0	0.3
12	8m - lyr	97.1	51.6
14	8m - lyr	87.9	3.2
1	1 yr +	78.6	11.5
2	1 yr +	86.1	96.5
10	1 yr +	91.3	93.2
13	1 yr +	91.4	0.6
Average		**89**	**28**

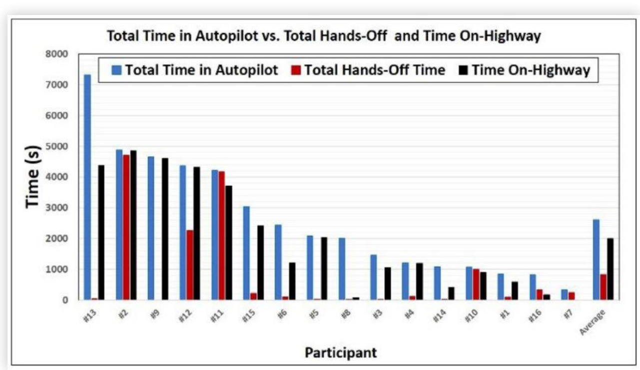
FIGURE 4 Participants' autopilot experience vs. percentage of hands-off while in autopilot



On-Highway/Off-Highway Autopilot Usage

Results also showed that participants were more likely to use autopilot while driving on highways (i.e. freeways). Specifically, participants used autopilot an average of about 70% on highway drives/trips. However, on non-highway trips (i.e. on secondary roads), participants used autopilot only about 7% of the time. This finding was not surprising as most participants had indicated earlier that they use autopilot in areas with visible lane lines/markings. This is one indication that the drivers developed some understanding of autopilot operation for lane keeping. Figure 5 shows total time in autopilot versus total hands-off time and time on-highway.

FIGURE 5 Total Time in Autopilot vs. Total Time On-Highway and Total Hands-off Time



Common driver deactivation of autopilot while driving on a highway included lane changes, approaching slow vehicles, lane merging or lane splitting, and exiting highways. On secondary roads, drivers deactivated autopilot when they wanted to change lanes, make a turn, or when approaching stop sign, traffic light, or stopped/slow vehicles.

Tasks Performed While Autopilot Is Active

Overall, participants engaged in a variety of tasks while autopilot was active during the observation period. However, these tasks were no different from the tasks they engaged in while autopilot was off. Typical tasks performed while autopilot was active include: (i) sending and receiving text messages, (ii) making and receiving phone calls, (iii) interacting with center console (navigation, music etc.), (iv) interacting with steering wheel buttons, (v) eating and drinking, (vi) talking to passengers. When performing non-driving related tasks, participants periodically looked at the road, splitting their visual attention until the task was complete. This is evident in the eye glance data discussed above. Most participants reported that they were comfortable looking away from the road somewhat longer because they were confident autopilot would act as "safety buffer" while their eyes were off the road.

Summary/Conclusions

The results reported in this study lead to several observations. First, participants felt responsible for the operation of their vehicles when autopilot was active because they did not think autopilot had the capability to drive without supervision. Second, eye glance analyses from the study showed that participants' eye on/off road glance behavior while operating a partially automated vehicle (i.e. Tesla autopilot) was somewhat similar to eye off-road glance behavior in radio tuning task while driving manually though substantially more variable. Nonetheless, drivers while in autopilot mode glanced away from the road scene no longer than about 4 s in the vast majority of instances. This finding is significant, since it contradicts the common perception that drivers will disengage from monitoring when operating a partially automated vehicle. Third, analysis of eye glance data and hands on/off steering wheel data showed that eyes on/off road glance behavior had no relation to whether drivers kept their hands on the steering wheel or not. Further, the level of experience (how long a driver has used autopilot) did not influence eye off-road glance behavior, neither did it influence hands on/off steering wheel behavior. The results indicated a bi-modal driver behavior when it comes to the operation of partially automated vehicles as observed in this study: those who mostly kept their hands on steering wheel while autopilot was active (i.e. *active drivers*) and those who mostly kept their hands off the steering wheel while autopilot was active (i.e. *supervisors*).

Study Limitations

This study required drivers to manually activate/turn on the video/audio capture system before each trip. Therefore, drivers were generally aware that they were being recorded during these trips, this could have influenced them to exhibit more appropriate behavior than they normally would.

Second, the study used drivers who owned Tesla vehicles, and may not be a good representation of the general driving population.

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