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Exploring Driver Adaptation to L2 Driving Automation Using Existing Naturalistic Driving Data

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16. Abstract

This project evaluated driver adaptation in the hours, days, and months after the introduction of SAE level 2 (L2) systems into the driving task. Three existing naturalistic driving study (NDS) databases were analyzed: the L2 Naturalistic Driving Study, the Virginia Connected Corridor Elite Naturalistic Driving Study, and the Older Driver Naturalistic Driving Study. To best assess driver adaptation, the analysis identified three phases of exposure time to L2 systems: Phase 1 (under 3 hours), Phase 2 (3 hours up to 8 hours), and Phase 3 (over 8 hours). The results suggested that driver adaptation was present for high-risk secondary tasks, as significant increases in engagement were observed over the three phases, but only when L2 systems were active. Additionally, drivers set their vehicle speed above the speed limit more frequently between Phases 1 and 2, with higher speeds set when L2 systems were active as opposed to when they were inactive.

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List of Abbreviations

ACC	adaptive cruise control
DDT	dynamic driving task
IRB	Institutional Review Board
L2	Level 2
L2 NDS	Naturalistic Study of L2 Driving Automation Functions
LC	lane centering
LOS	level of service
MGOR	mean glance off-road
NDS	Naturalistic Driving Study
NORG	number of off-road glances
RTI	requests to intervene
SAE	SAE International (In 2006 the name was changed from Society of Automotive Engineers)
SHRP 2	Second Strategic Highway Research Program
SLG	single longest off-road glance
TD	traffic density
TEORT	total eyes-off-road time
TOD	time of day
VCC50 Elite	Virginia Connected Corridor 50 Elite Vehicle
VTTI	Virginia Tech Transportation Institute

Executive Summary

In the driving domain, the concept of behavioral adaptation refers to how humans respond intentionally or unintentionally to new technology that serves a specific driver need (Manser et al., 2005). While behavioral adaptation and user reliance can occur as a result of changes to any aspect of the roadway system, the present study is concerned specifically with how drivers initially adapt their behaviors to Level 2 (L2) systems as defined by SAE International (SAE J3016, 2021). SAE J3016 defines L2 systems to be the combination of both lateral and longitudinal control system support for the driver (e.g., steering and acceleration/braking). To gain insight into driver adaptation to L2 systems, driver behavior while using these systems must be observed and measured. Using frequency distributions generated from the naturalistic driving databases used for these analyses, this study operationally defined these three phases of experience or exposure phases using L2 systems as:

Phase 1: defined as under 3 hours of L2 experience;

Phase 2: defined as from 3 to 8 hours of L2 experience; and

Phase 3: defined as over 8 hours of L2 system experience.

Two analyses were conducted that used existing naturalistic driving data to assess driver adaptation to L2 systems for middle-age and older drivers. The first study used two naturalistic driving study databases of middle-age drivers that compared behavior during the first weeks of driving with L2 systems (L2 NDS; participants 25 to 54 years old) to the behavior of drivers who had owned and driven vehicles with L2 systems for several months (Virginia Connected Corridor Elite NDS; participants 22 to 77 years old). The second study compared the behavior of older drivers (70 to 79) during their first weeks of driving with L2 systems to the behavior of middle-age drivers (25 to 54) during their first weeks of driving with L2 systems. These four research objectives were evaluated for both studies:

Research Objective 1: Evaluate driver strategies and behaviors for maintaining vehicle safety while using L2 systems over time.

Research Objective 2: Determine what factors influence how drivers rely on and adapt to L2 systems.

Research Objective 3: Determine whether there are relevant outcomes of adaptation and reliance upon L2 systems.

Research Objective 4: Identify lessons learned from drivers using L2 systems in vehicles.

Study 1: Driver Adaptation to L2 NDS Over Time

Method

Overview of Naturalistic Driving Study Databases

This study evaluated driver adaptation to L2 systems using data from two NDSs: (1) the Naturalistic Study of L2 Driving Automation Functions (L2 NDS) representing inexperienced L2 drivers; and (2) the VCC50 Elite NDS representing experienced L2 drivers. Each database included a variety of makes and models that are reported in Appendix A.

The L2 NDS database (Russell et al., 2018) was used to assess driver adaptation to L2 systems over the course of each driver's initial 4 weeks of driving a vehicle with those features present. In the original study, 120 participants drove study-provided vehicles, which were different from those they currently owned. From the original 120 participants, the current project used 82 participants, who had a minimum of 3 hours of cumulative driving time with L2 systems active.

The VCC50 Elite NDS database was used as a comparison group of experienced participants. In the original study that produced the VCC50 Elite NDS database, 50 participants owned personal vehicles that had L2 systems and had driven them for several months to over a year. From the original 50 drivers, the current project used 33 drivers, whose vehicles: (a) had both adaptive cruise control and lateral control (e.g., lane centering, LC); and (b) had data to indicate L2 system state was available.

NDS Variables

To assess driver strategies and behaviors used to maintain vehicle safety while using L2 systems, speed selection at moment of L2 feature engagement as well as driver engagement in secondary tasks were used for analysis. Speed selection at moment of L2 feature engagement was determined using database coding algorithms. Every time the driver engaged L2 systems, the speed at which the vehicle was traveling was coded and marked as was the posted speed limit.

To better assess the type of behaviors that drivers engage in when using L2 systems, trained data coders reviewed randomly selected matched cases (when L2 systems were active) as well as controls (when L2 systems were available but inactive) to determine prevalence of secondary task engagement. These secondary task types were grouped into those types of tasks that are high risk (e.g., texting on mobile phone) or low risk (e.g., adjusting radio). High-risk tasks were those tasks that were found to be associated with increased crash risk in the Dingus et al. (2016) analysis using the Second Strategic Highway Research Program NDS database. The low-risk tasks were not found to be associated with an increase in crash risk in the same analysis. Additionally, frame-by-frame location of eye glances were recorded by trained data coders and duration of eyes-off-road time was also calculated when L2 systems were active versus when they were available but inactive.

Results

Speeding Behavior

When L2 systems were available and active, inexperienced L2 drivers (i.e., from the L2 NDS dataset) selected speeds that were above the speed limit more frequently than when L2 systems were available and inactive, and the difference was statistically significant with $p < .001$. On average, the selected speed was 4.56 mph higher, when systems were available and active. Similarly, experienced L2 drivers (i.e., from the VCC50 Elite NDS) also selected higher speeds when L2 systems were available and active than when systems were available and inactive, and this difference was also statistically significant with $p < .001$. On average, the selected speed was 2.66 mph higher, when systems were available and active.

Secondary Task Engagement

This study also examined the prevalence of secondary task engagement. For inexperienced drivers in the L2 NDS dataset, analyses of high-risk secondary task engagement found a statistically significant interaction between L2 system activation (i.e., available and active versus available and inactive) and exposure to active L2 systems (i.e., Phase 1 – 0 to 3 hours of exposure; Phase 2 – 3 to 8 hours of exposure; Phase 3 – 8+ hours of exposure), $p = .005$. While the prevalence (i.e., the percentage of epochs) of high-risk secondary task engagement increased over time when L2 systems were active (i.e., from 9.5% in Phase 1 to 14.1% in Phase 3), it decreased over time, when L2 systems were available but inactive (i.e., from 13.5% in Phase 1 to 7.2% in Phase 3).

Eye Glance

This study also examined the prevalence of eyes-off-road time. For inexperienced drivers in the L2 NDS dataset, there were consistent effects when L2 systems were available and active, such that eyes off roads glances were higher for total glance duration (3.16 versus 2.07 seconds; $p < .001$), mean glance duration (1.03 versus 0.80 seconds; $p < .001$), and single longest glance duration (1.38 versus 0.99 seconds; $p < .001$). There was no statistically significant difference finding for the number of glances, p = p = .082.

Most interestingly, there was a significant interaction between L2 system activation and exposure over time to active L2 systems (i.e., Phase 1 – 0 to 3 hours of exposure; Phase 2 – 3 to 8 hours of exposure; Phase 3 – 8+ hours of exposure). Specifically, this was statistically significant for total glance duration ($p < .001$), mean glance duration ($p = .03$), single longest glance duration ($p = .04$), and the total number of glances ($p = .006$). All of the measures demonstrated similar trends, where the differences increased over time, such that the eye glance metrics were always greater when systems were active (versus inactive) during Phase 3. When L2 systems were active (versus inactive), the significant interactions demonstrated that:

- the total glance duration was 0.32 seconds longer during Phase 1 and increased to 2.29 seconds during Phase 3;
- the mean glance duration was 0.13 seconds longer during Phase 1 and increased to 0.38 seconds during Phase 3;
- single longest glance duration was 0.24 seconds longer during Phase 1 and increased to 0.65 seconds during Phase 3; and
- total number of glances were 0.03 lower during Phase 1 but increased to be 1.15 higher during Phase 3.

Study 2: Driver Adaptation to L2 by Driver Age

Method

Liang et al. (2019) conducted an NDS with 18 older drivers 70 to 79 years old. Participants drove one of four vehicles equipped with both lateral and longitudinal L2 assistance features for 6 weeks each. Participants were eligible for the study if they had not owned or regularly driven a vehicle that had either lateral or longitudinal L2 assistance features.

Matched samples were used to assess selection of speed when L2 systems were active versus available but inactive. For eye glance (e.g., eyes-off-road time) and secondary task behavior, analyses used the matched sample of cases plus control segments, which were randomly selected segments of video when L2 systems were active (cases) and matched sample segments of video when L2 systems were available but inactive (control).

NDS Variables

Similar dependent variables were used to compare middle-age (L2 NDS) and older (Older Driver NDS) driver strategies and behaviors. Speed selection at initiation of L2 systems and secondary task engagement were assessed as part of these analyses.

Results

The total driving time was shorter for older drivers (Older Driver NDS) than middle-age drivers (L2 NDS). While all middle-age drivers selected from the L2 NDS surpassed 3 hours of experience with L2 systems active, the maximum duration of active L2 experience in the Older Driver NDS was less than 3 hours. This expected result is important in that older drivers drove less overall and also drove less with L2 systems active than did the middle-age drivers. Thus, the remainder of these results compare the older drivers (Older Driver NDS) to only Phase 1 (first 3 hours of driving experience with L2 active) for middle-age drivers (L2 NDS).

Speeding Behavior

The analysis of speeding behavior compared: (a) older drivers to middle-age drivers and (b) L2 system status. When L2 systems were available and active, drivers selected speeds that were above the speed limit more frequently than when L2 systems were available and inactive, $p < .001$. Drivers selected speeds were 4.4 mph higher, when systems were available and active. There was also a statistically significant difference between older drivers and middle-age drivers ($p < .01$), where middle-age drivers selected speeds that were 5.2 mph faster than older drivers. While the older drivers in the Older Driver NDS did not select speeds over the speed limit as frequently as the middle-age drivers in the L2 NDS, the frequency of selecting a speed that was over the posted speed limit was significantly more common when L2 was active than when it was available but inactive for older drivers (Older Driver NDS).

Secondary Task Behavior

The results from the secondary task analysis indicated that the middle-age drivers engaged in secondary tasks (i.e., 63% of observations) more than the older drivers (i.e., 57% of observations), when L2 systems were active ($p = .04$). For high-risk secondary tasks, the older drivers did engage in this type of behavior at similar rates to middle-age drivers (L2 NDS) when L2 systems were active (10% of matched samples), but older drivers engaged in secondary tasks more frequently than middle-age drivers ($p = .03$), when L2 systems were available but inactive (8%). These are surprising results, as previous NDSs have found that older drivers have much lower prevalence of high-risk secondary tasks than middle-age drivers (Guo et al., 2016).

Eye Glance

The results from the eye-glance analysis found a consistent main effect, where middle-age (L2 NDS) drivers looked away from the forward roadway for longer periods of time (i.e., longer eyes-off-road time) than did the older drivers (Older Driver NDS) for total glance duration (0.68 seconds longer, $p = .01$), mean glance duration (0.15 seconds longer, $p = .007$), single longest glance duration (0.24 seconds longer, $p = .028$), and number of glances (0.44 more glances, $p = .035$). When L2 systems were available and active, the effects were mixed, such that eye-off-road glances were only higher for mean eyes off road glance duration (0.06 seconds longer, $p = .003$) and single longest off-road glance (0.10 seconds longer, $p = .003$).

Conclusions From Study 1 and Study 2

Overall, the results from these analyses indicate that driver selection of higher speeds and high-risk secondary task engagement increased with use of L2 systems. Eye glance data (e.g., eyes-off-road time) showed that drivers looked away from the road more with increased use of L2 systems. This analysis evaluated time of day, weekday versus weekend, and road type and was unable to identify a specific condition under which drivers were more likely to use L2 systems. A more nuanced, higher-level analysis may be able to capture these differences if they exist, but this would require additional data coding and/or algorithm development.

The analyses comparing older drivers' use of and adaptation to L2 systems showed several key results. First, older drivers chose to drive with L2 systems much less frequently than the middle-age drivers in the L2 NDS dataset. This may have been due to the difference in purpose of trips. The middle-age drivers (L2 NDS) were more often commuting into and out of a large metropolitan area; thus, they tended to drive more frequently than other adult commuters in more suburban/rural locations. This may also have been due to older drivers driving less frequently on controlled-access roadways for a variety of reasons, although they were equally likely to activate L2 systems on both controlled and non-controlled access road types (the chi-square analysis of road type and driver group was not significant).

Additionally, due to the low amount of driving with L2 systems active, these analyses were unable to assess driver adaptation for older drivers. Studies that investigate older drivers' interactions with new vehicle technologies would benefit from a data collection period longer than six weeks and potentially from recruiting older drivers who have purchased these types of vehicles, as this may increase the likelihood that the drivers will use the systems more frequently.

This analysis was specifically designed to assess how driver behaviors change over time after the introduction of L2 system technologies compared to when the systems were available but inactive. This study was not a risk analysis and thus, whether or not the behaviors assessed with L2 systems active in this report increase crash occurrence is currently unknown. Note that safety-critical events were not evaluated, only the prevalence of driver behaviors over time.

The analyses attempted to control for the roadway environment using matching criteria; however, these controls were not perfect. Additional detailed data coding and/or algorithm development would be beneficial to furthering our understanding of the importance of roadway context with L2 use.

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Study 1: Driver Adaptation to L2 Systems Over Time

Introduction

Behavioral Adaptation

In the driving domain, the concept of behavioral adaptation refers to how humans respond, either intentionally or unintentionally, to the introduction of a new technology that serves a specific driver need (Manser et al., 2005). Human factors researchers have been concerned with behavioral adaptation since it was first introduced in a report published by the Organization for Economic Coordination and Development (OECD, 1990). Kulmala and Rämä (2013) modified the original definition to more broadly capture behavioral adaptation as "the collection of any driver, traveler, and travel behavior that occurs following user interaction with a change to the road traffic system, in addition to those behaviors specifically and immediately targeted by the initiators of the change."

More general theories of behavioral adaptation focus on risk-based measures, beginning with a study of changes in galvanic skin response during driving by Taylor (1964), which led to further investigations of behavioral adaptation and integration of the theories of risk compensation and risk homeostasis (Kulmala & Rämä, 2013). Risk compensation and risk homeostasis theories function under the principles of a perception-evaluation process: (1) people have an idea of the level of risk that they are willing to tolerate; (2) people also have a "target" level of risk at which they are most comfortable; and (3) people have a reasonably good ability to perceive their current level of risk. With the notable exception of the zero-risk theory (Summala, 1988), risk compensation theories neglect to explicitly consider learning and time. However, the zero-risk theory posits that drivers' target level of risk can change with learning over time, which is where driver adaptation may occur (Kinnear & Helman, 2011).

Risk allostasis theory builds on the zero-risk theory to incorporate driver perception and decision making along with the constant changes that occur in the environment (i.e., learning over time; Kinnear & Helman, 2010). While risk homeostasis considers a static, acceptable level of risk, allostasis is more dynamic in that it assumes that an individual's accepted level of risk can change both over time as well as according to the context of the situation. While learning is included in this theory, constant change, including motivation, may affect a driver's perceived acceptable risk. For example, when drivers are late for work, their motivation to gain lost time may change their perception of the "acceptable risk" of traveling above the speed limit.

Kinnear and Helman (2010) used risk allostasis theory to evaluate and potentially predict behavioral adaptation for drivers using driver assistance technologies (SAE J3016). Their assessment incorporates the driver's feelings of risk, task difficulty, and workload. They maintain that with sufficient sensitivity to risk, task difficulty, and workload, risk allostasis theory predicts that any alteration of the driving task (e.g., partial automation) will result in driver adaptation that will trend toward maintaining task demand within a preferred range. In other words, as the automated driving features simplify the driving task, the driver will feel free to increase task demand in a variety of ways that could include increased speed, increased secondary task engagement, and decreased following distance. Thus, risk allostasis theory predicts that the use of partial driving automation technologies would result in increased trust and reliance on them. When higher levels of trust are placed in these features, the operator may become complacent (Singh et al., 1993a, 1993b). These issues have often been attributed to an operator's tendency to reduce their monitoring of highly reliable automated driving features (Parasuraman, Sheridan, & Wickens, 2008). This claim was substantiated by Llaneras et al. (2013), who showed that, when given the opportunity to relinquish control of lateral and longitudinal operations to a simple but reliable automated system, most drivers will engage in moderate to complex secondary tasks and will also exhibit increased eyes-off-the-forward-road time.

Furthering this line of research, a driving simulator study was conducted to investigate if differences existed in the secondary-task engagement of novice and experienced drivers both with and without driver assistance technologies (He & Donmez, 2019). With driver assistance technologies, novice drivers had a higher manual interaction rate with an in-vehicle display than experienced drivers. Furthermore, experienced drivers had shorter average glance durations toward the display than novice drivers in general, but the difference was larger when using driver assistance technologies than with manual driving. From this study, it appears that with partial driving automation technologies, experienced drivers are more conservative in their secondary-task engagement behaviors compared with novice drivers. There could be two possible implications of this research. First, it is possible that this effect could generalize to inexperienced users of partial driving automation technologies, in which experienced users engage in secondary tasks less than inexperienced users of these technologies. Second, it could also suggest that adolescents show more egregious eye glance behavior while using partial driving automation technologies than adult drivers, though they also exhibit poor eye glance behavior. Thus, partial driving automation technologies could be particularly problematic for adolescent drivers while they are learning to drive.

While behavioral adaptation and user reliance can occur as a result of changes to any aspect of the roadway system, the present study is concerned specifically with how drivers initially adapt their behaviors to Level 2 (L2) systems, as defined by SAE International (SAE J3016, 2018). L2 systems assist the driver by using a combination of adaptive cruise control and lane centering to provide longitudinal and lateral control of the vehicle, respectively. When operated without other traffic in the driver's travel lane, ACC is used to maintain vehicle speed in a manner like that of conventional cruise control. However, if the driver approaches a slower moving or decelerating lead vehicle in their travel lane, ACC will attempt to reduce the speed of the driver's vehicle to that of the lead vehicle. In many driving situations, this results in the driver's vehicle following the lead vehicle at a prescribed following distance, or headway. Some ACC systems also have an ability to follow the lead vehicle to a complete stop; however, a constant headway is not typically maintained at very low speeds (i.e., approaching zero). Lateral features such as LC provide sustained lateral assistance using sensors to determine the location of lane lines on either side of the vehicle and will attempt to keep the driver's vehicle in the center of the travel lane.

Both longitudinal and lateral control features are currently available on a wide variety of vehicles, and a growing number of these types of features will continue to enter the market in the near future. The following sections further discuss the control features of interest for this study and the terminology used to describe them.

Defining and Categorizing Driving Automation Systems

Assessing the effects of L2 systems requires an understanding of how they are defined. In SAE's (2021) *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*, it defines driving automation system features and clarifies the types of *active safety systems* that are not considered part of the taxonomy of vehicle systems. The term *active safety systems* refers to a broad array of features, which include electronic stability control and automatic emergency braking. In contrast, the term *L2 systems* refers to the activation of both ACC and LC. The term *L1 feature* refers to either a longitudinal or lateral control system, but not both.

This analysis focused on understanding driver adaptation to L2 systems. L2 systems are typically manually activated (usually above a certain speed) and fundamentally change the task of the driver for the period of time that they are active. Given that the task of driving may fundamentally be changed with L2 systems active, the base level of risk of driving may also be changed. This analysis is focused on assessing whether we can observe changes in behavior that may be occurring due to the introduction of L2 systems. Whether these behaviors contribute to crash risk could not be addressed in the present analysis due to insufficient numbers of safety outcomes (crashes, near-crashes, etc.); thus, we did not evaluate actual risk that may be associated with these driver adaptation behaviors.

Adaptation to Driving Automation Features

Although L2 systems are increasingly available in vehicles sold in the United States (AAA, 2019; Consumer Reports, 2019), based on a 2016 survey (Bureau of Transportation Statistics, 2017), light vehicles driven in the United States were on average 12 years old. Therefore, it will likely take another decade before these systems reach substantial levels of market penetration in the United States. Given their growing availability, it would be beneficial for human factors researchers get ahead of this curve and develop a broad understanding of how drivers, over a range of ages and driving experience, use and activate these L2 systems. Moreover, there is value in conducting research to understand the environmental conditions under which these systems are activated, whether these systems affect driver behaviors, and how these effects occur. While Grove et al. (2016) assessed the adaptation of truck drivers to crash avoidance systems, driver adaptation to the systems over time was unclear, and adaptation in light vehicle drivers was not addressed. The present study used naturalistic driving data collected from previous studies conducted by the Virginia Tech Transportation Institute to assess light vehicle drivers' use of L2 systems.

Learning theory suggests that with increased practice comes improvement in performance as a function of the power law of practice (Newell & Rosenbloom, 1980). Figure 1 displays the pattern in which acquisition of a new skill occurs as the user gains experience. The greatest amount of new learning occurs during the early stages, when the user is initially gaining experience. Learning then follows an exponential curve, continuing but at a decreased rate.

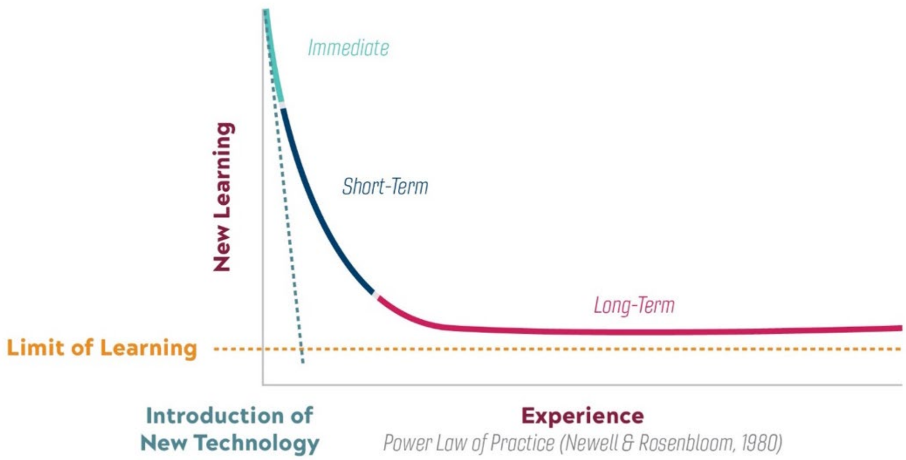


Figure 1. Depiction of immediate, short-term, and long-term phases of behavioral adaptation as plotted on a traditional learning curve (adapted from Newell & Rosenbloom,1980)

By evaluating driver behavior for varying durations of experience with L2 systems, we can assess the moments when driver behavior may change most rapidly (immediate and short-term exposure) compared to when driver behavior may change much more slowly or is fairly stable after long-term use (Manser et al., 2013).

In light of this anticipated pattern of learning, we hypothesized that most behavioral adaptation to L2 systems would occur in the initial periods of use. Therefore, to gain insight into driver adaptation to L2 systems, it was necessary to observe and measure driver behavior while using these systems over time.

Objectives

Four research objectives were defined for this driver adaptation study:

> **Research Objective 1:** Evaluate driver strategies and behaviors for maintaining vehicle safety while using L2 systems over time.
>
> **Research Objective 2**: Determine what factors influence how drivers rely on, and adapt to, L2 systems.
>
> **Research Objective 3:** Determine whether there are relevant outcomes of adaptation and reliance upon L2 systems.
>
> **Research Objective 4:** Identify lessons learned from drivers using L2 systems in vehicles.

The first section of the report presents Study 1, which used two databases from previous studies to address these four objectives for adult drivers (22 to 77 years old). In Study 2, an additional dataset was used to address the same objectives for older drivers (70 to 79 years old).

Method

Overview of Naturalistic Driving Study Databases

This study evaluated driver adaptation to L2 systems using data from two naturalistic driving studies (NDSs): (1) the Naturalistic Study of L2 Driving Automation Functions (L2 NDS) representing inexperienced L2 drivers and (2) the VCC50 Elite NDS representing experienced L2 drivers. The L2 NDS (Russell et al., 2018) assessed driver adaptation to L2 systems over the course of each driver's initial 4 weeks of driving a vehicle with those features present. In the L2 NDS, participants drove study-provided vehicles which were different from those they currently owned, so this analysis works from the assumption that participants in this dataset had little to no experience with the specific L2 systems present on the research vehicle.

The VCC50 Elite NDS was used as a comparison group of experienced participants. In this study, 50 participants owned personal vehicles with L2 systems and had driven them for several months to over a year.

Inexperience L2 Drivers (L2 NDS)

In the L2 NDS, 120 participants were recruited from the Washington, DC, metro area and drove one of 10 instrumented vehicles equipped with market-available lateral and longitudinal driving feature systems. These instrumented vehicles were "on loan" to the participants for the duration of the data collection period. Appendix A lists the specific year and package information for each vehicle.

Although 120 drivers participated in the L2 NDS, only 82 had sufficient driving time with L2 systems active (greater than 3 cumulative hours) for use in the present analyses. Additionally, 16 of these 82 participants were drivers of Volvo vehicles. The Volvo vehicle automatically engaged level 1 features when driving above a set speed (i.e., the Volvo automatically activated LC above a certain mile per hour and could not provide a comparison for "available but inactive"). Therefore, these 16 participants were excluded from analyses where the data could not be effectively parsed between L2 active and L2 available but inactive (neither lateral nor longitudinal vehicle control were active). Appendix A provides tables for the number of participants assigned to each vehicle across all datasets and for lateral and longitudinal driving features for each vehicle model.

Experienced L2 Drivers (VCC50 Elite NDS)

The VCC50 Elite dataset contains data from 50 drivers of vehicles equipped with at least longitudinal control systems (ACC), although many also had some form of lateral control systems, and these were the participants ultimately selected for the study. The 50 participant drivers' personal vehicles were instrumented with data acquisition systems similar to those used in the L2 NDS. Appendix A has the list of specific vehicle makes and models included in this dataset, as well as the vehicles with lateral and longitudinal vehicle control. The VCC50 Elite NDS drivers provided an important comparison group of drivers with long-term exposure to L2 systems (in contrast to the L2 NDS drivers, who drove vehicles different from their own during the research study). Participants in the VCC50 Elite NDS were recruited and primarily commuted in the Washington, DC, metro area (which includes Northern Virginia and sections of Maryland).

Of the 50 drivers in the VCC50 Elite dataset, only 33 drivers had vehicles with both lateral and longitudinal control systems. Of these 33 drivers, only 19 had L2 system status data available using an in-house developed machine vision algorithm. These drivers were those whose vehicles had both ACC and some form of lateral vehicle control system. Table 1 shows the number of participants and demographics for the data subsets used for the analyses.

Table 1. Summary of Participant Demographics Selected for Sample

	Inexperienced L2 Drivers (L2 NDS)	**Experienced L2 Drivers (VCC50 Elite NDS)**
Number of participants	82	33
Mean participant age (SD) [years]	40.13 (8.32) [25–54]	47.6 (12.5) [22–77]
Distribution	M: 48 F: 37	M: 25 F:8

NDS Variables

Table 2 and Table 3 describe the independent and dependent factors, respectively, that were examined using the L2 NDS dataset. For the independent variables, the variable L2 System Status was split into two critical states: L2 system active and L2 system available but inactive. These two periods of driving time represented: (1) periods when L2 systems were actively engaged, and (2) periods when L2 systems were available to the driver but the driver chose to not engage them. These were the only two periods of driving time evaluated in these analyses. When the vehicle was traveling too slowly for the L2 systems to become available, this driving time was largely removed from the analyses. For the L2 NDS dataset with inexperienced L2 drivers, the respective vehicle manufacturers supported the project by providing the codes to use of the onboard vehicle network. Through this access, the research team could determine when L2 systems were available for use by a driver and code L2 system status as active versus available but inactive. One caveat to this is that if an L2 feature was unavailable due to weather conditions or poor lane markings, this driving time would have simply been coded as "available but inactive," as there was no method for us to decipher the vehicle system state at this level of detail.

The duration of driving time with L2 systems active is also a critical independent variable throughout these analyses. This variable, referred to as L2 exposure phase, is an exposure metric that divides cumulative driving time with L2 systems active into three phases.

- Phase 1: the initial 3 hours
- Phase 2: the time period from 3 to 8 hours
- Phase 3: any driving time beyond 8 hours

This exposure metric only refers to drivers inexperienced with L2 systems from the L2 NDS. We did not expect to see differences in driving behavior over time for the experienced drivers in the VCC50 Elite NDS dataset; therefore, there is only one exposure category for this dataset—long-term exposure to L2 systems. Note that the drivers in the VCC50 Elite dataset had owned their L2-equipped vehicles for a minimum of 3 months to over several years, and therefore represent a wide variety of longer-term experience levels than drivers of vehicles in the L2 NDS analysis.

The variable L2 Activation Group was added after some preliminary analyses suggested that there may be some systematic differences in the drivers who accumulated over 8 hours of L2 system activation time and those drivers who accumulated less than 8 hours of L2 system activation. This variable was used in all statistical models that were conducted to ensure that any significant results were not due to potential differences in these two groups of drivers.

The remaining independent variables, listed in Table 2, are those that relate to the environmental conditions under which drivers engaged L2 systems. These environmental conditions included time of day, day of week, traffic density, weather condition, and road type. Please note that these variables are defined the same way for both studies. Some of these variables were obtained directly from the dataset (TOD, day of week, road type, time in study), whereas traffic density and weather were derived by analysts carefully reviewing designated trip file videos.

Table 2. Independent Factors

Factor	**No. of Levels**	**Description for Inexperienced Drivers (L2 NDS)**	**Description for Experienced Drivers (VCC50 Elite NDS)**
L2 System Status	2	• Active: Both lateral and longitudinal vehicle motion control subtasks of the dynamic driving task (DDT) were being controlled by the L2 systems. • Available but inactive: Both lateral and longitudinal vehicle motion control subtasks of the DDT were being controlled by the human driver.	• Active: Both lateral and longitudinal vehicle motion control subtasks of the DDT were being controlled by the L2 systems. • Available but inactive: Both lateral and longitudinal vehicle motion control subtasks of the DDT were being controlled by the human driver.
L2 Exposure Phase (Phase)	3/1	• Phase 1: Cumulative duration of less than 3 hours of driving time with L2 automated features activated. • Phase 2: Cumulative duration of between 3 hours and 8 hours of driving time with L2 automated features activated. • Phase 3: Cumulative duration of over 8 hours of driving time with L2 automated features activated.	• Long Term Exposure: From 3 months of driving a vehicle with L2 systems through 2.5 years of driving a vehicle with L2 systems.

Factor	No. of Levels	Description for Inexperienced Drivers (L2 NDS)	Description for Experienced Drivers (VCC50 Elite NDS)
L2 Activation Group	2/1	• Longer L2 activation: Those drivers who activated L2 for over 8 hours within 4 weeks of study duration. • Shorter L2 activation: Those drivers who activated L2 for less than 8 hours within 4 weeks of study duration.	• Long-Term Exposure: These drivers will not be split into separate groups as their behaviors are considered stable over time.
Time of Day (TOD)	7	• 5 a.m.–8 a.m. • 8 a.m.–12 p.m. • 12 p.m.–4 p.m. • 4 p.m.–7 p.m. • 7 p.m.–10 p.m. • 10 p.m.–1 a.m. • 1 a.m.–5 a.m.	• 5 a.m.–8 a.m. • 8 a.m.–12 p.m. • 12 p.m.–4 p.m. • 4 p.m.–7 p.m. • 7 p.m.–10 p.m. • 10 p.m.–1 a.m. • 1 a.m.–5 a.m.
Day of Week (Weekday/Weekend)	2	• Weekday (Monday–Friday) • Weekend (Saturday–Sunday)	• Weekday (Monday–Friday) • Weekend (Saturday–Sunday)
Traffic Density (TD)*	2	• Level of Service (LOS) A & B (Free flow with little restriction on speed selection) • LOS C–F (Some restriction of speed selection through stop-and-go traffic)	• Level of Service (LOS) A & B (Free flow with little restriction on speed selection) • LOS C–F (Some restriction of speed selection through stop-and-go traffic)
Road Surface	2	• Clear/dry • Wet (includes snow, ice, sleet, etc.)	• Clear/dry • Wet (includes snow, ice, sleet, etc.)
Road Type	2	• Interstate/controlled-access highway • Uncontrolled-access highway, arterial, residential	• Interstate/controlled-access highway • Uncontrolled-access highway, arterial, residential

*This variable was not applied to the Older Driver Analysis.

The dependent variables that were assessed are listed in Table 3 below. These metrics are organized into four groups: (1) Exposure Metrics, (2) Matched Sample of Cases when L2 Systems are Active and Matched Controls, (3) L2 System Activation Segments, and (4) Safety Outcomes. The first group, Exposure metrics, is a dependent measure to assess the percentage of time that L2 systems were active. Exposure metrics, which divides cumulative driving time with L2 systems active into three phases, was described above.

The second group of metrics involves matched cases. As part of the original L2 NDS, a random sample of cases when L2 systems were active was identified and reviewed by trained coders. Once the cases were identified, a matched sample of controls was identified when the L2 systems were available but inactive (see Table 3). Each case and each matched control were 15 seconds in duration. As part of this research effort, additional matched sample cases and controls were added to the dataset and these matched samples were coded by trained data coders. The sampling strategy for these matched samples is described below in detail. The key data obtained from these matched samples included specific driver behaviors such as types of secondary task engagement as well as 15-second epochs of continuous eye-glance location coding.

The third group, Activation of L2 systems, was obtained by identifying the moment when a driver chose to engage the L2 systems. For an instance of L2 activation to be included, the driver had to have the L2 systems engaged for no less than 120 seconds to ensure that the activation was not a mistake by the driver or spurious data in the data stream. For comparison purposes, a random sample of a 120-second segment of driving when L2 systems were available but inactive was also created. This comparison sample was matched on the following criteria: (1) driver ID, (2) vehicle speed above 40 mph, (3) TOD (±2 hours of when L2 system was active), (4) day of week (weekday versus weekend), (5) different trip from the trip in which L2 systems were activated.

The fourth group of dependent variables is safety outcomes. In NDSs, safety outcomes are usually operationally defined as crashes, near-crashes, or safety-critical events. A limiting factor for the research was that these two NDSs were fairly small, and thus even a combination of the crashes and near-crashes was not large enough to allow for meaningful analyses. For the L2 NDS, the vehicle network data did allow for a precise measure of requests to intervene (RTIs) by the L2 systems. RTIs include moments when a driver may not have at least one hand on the steering wheel and the system presents a visual/auditory alert indicating that a hand must be on the steering wheel. If the driver does not comply within a period of time, the vehicle will shut down the L2 systems and will only allow the driver to re-engage them when the vehicle has come to a stop and the ignition has been cycled (on/off). Unfortunately, RTIs were not available in the VCC50 Elite NDS (i.e., for experienced L2 drivers), so any analyses with RTIs could only be conducted with inexperienced L2 drivers in the L2 NDS dataset.

Table 3. Dependent Measures

Metric	Operational Definition	Number of Participants
Exposure Metrics		
Percent L2 System Exposure	Hours L2 system was active/(hours L2 system was active + hours L2 system was available but inactive)	$N = 82$

Metric	Operational Definition	Number of Participants
	*Volvos excluded because denominator in calculation is not the same as other vehicles since lateral control turned on automatically	
Matched Sample of Cases When L2 Systems Were Active + Control Segments When L2 Systems Were Available but Inactive		
Eye Glance Behaviors	Fifteen-second samples of driving time in which driver's eye location was continuously coded by trained data coders. The following metrics were calculated based upon this continuous time series data coding (see also Table 7): • Single longest glance duration (s) • Total number of off-road glances • Total duration of off-road glances (s) • Mean duration of each off-road glance (s) • Glance to instrument cluster	N = 82
Secondary Task Engagement	When drivers engage in a task that is not critical to the safe operation of a vehicle. The specific types of tasks that were coded were grouped by high risk, low risk, or no secondary task present. High risk versus low risk was determined based on Guo et al. (2016; https://doi.org/10.1093/ije/dyw234), which used data collected in the SHRP 2 NDS. Secondary task crash risk analyses were grouped as follows: • High risk secondary task (those tasks that were associated with crash occurrence) versus low-risk secondary task (those secondary tasks that were not associated with crash occurrence) plus no secondary task present. • Any secondary task present (both high risk and low risk) versus no secondary task present.	N = 82
Metrics for L2 Activation		
Vehicle Speed at Moment of L2 Activation	Vehicle speed (mph) at the moment that driver chose to engage L2 systems.	N = 82
Vehicle Speed for Matched Sample When L2 System Was Available but Inactive	Vehicle speed (mph) for moments in time when L2 systems are available but inactive. This sample represents a 1:1 match with the sample when drivers choose to activate L2 systems. (The set of matching criteria used are described on previous page).	N = 82
Road Type at Moment of L2 Activation/Matched Sample	The type of roadway (either controlled-access or uncontrolled-access roadway) the driver was	N = 82

Metric	Operational Definition	Number of Participants
When L2 System Was Available but Inactive	traveling at the moment they chose to activate L2 system.	
Road Type at Moment of L2 Activation/Matched Sample When L2 System Was Available but Inactive	The type of roadway (either controlled-access or uncontrolled-access roadway) the driver was traveling for matched sample when L2 system was available but inactive.	N = 82
Safety Outcomes		
RTIs	Rate of L2 system-initiated RTIs to the driver (only available for the L2 NDS dataset) per mile traveled with L2 systems active.	N = 82

Note: L2 NDS sampling for matched sample of cases (L2 systems active) + control segments (L2 systems available but inactive).

The team implemented a sampling plan designed to determine if there is driver adaptation over time while using L2 systems. Given that we are interested in identifying learning over time, the sampling plan was designed to best assess the earliest moments of exposure to the L2 systems (i.e., learning curve as discussed in the introduction; see Figure 1). This sampling plan was designed to over-sample the steepest section of this learning curve to evaluate how driver behavior changes during this critical time.

The sampling strategy adopted for the L2 NDS dataset resulted in a final matched sample (when L2 systems were active) that frequently sampled (four samples per hour) for Phase 1, moderately sampled (two samples per hour) for Phase 2, and less frequently sampled (one sample per hour) for Phase 3. The control segments (when L2 systems were available but inactive) were identified and followed the same sampling strategy (matching criteria described below). Cumulative exposure to L2 systems was used because each participant had a different number of hours of exposure when L2 systems were active. The sampling rate was ultimately determined by optimizing the resources available for data coding a total of 2,000 matched samples (see Table 4 for sampling rate details). The final matched sample dataset incorporated the matched samples coded from the original NHTSA L2 NDS project (Contract No DTNH22-14-D00328L, Task Order #1) as well as the additional 2,000 samples coded as part of this NHTSA contract.

Table 4. Sampling Rate Per Phase of Cumulative L2 Driving Exposure

Cumulative Exposure Phase	Sampling Rate for Matched Sample of Cases (L2 systems Active)	Sampling Rate for Control Segments (L2 systems Available but Inactive)
Up to first 3 hours of L2 exposure	4 per hour	4 per hour
Hours 3 through 8 of L2 exposure	2 per hour	2 per hour
Over 8 hours of L2 Exposure	1 per hour	1 per hour

The research team examined the number of hours of L2 system exposure and determined that 100 percent of the participants had a minimum of 3 hours of cumulative L2 exposure and approximately 50 percent of the participants had over 8 hours of cumulative L2 exposure. Because there were some participants who did not have sufficient numbers of matched controls (where L2 was available but inactive), some of the analyses concentrated on two phases: less than 8 hours and greater than 8 hours of L2 system exposure.

As part of the L2 NDS, L2 system state was determined using information available from the vehicle network information. As such, the database contained continuously coded data indicating whether the L2 systems were active, available but inactive, or unavailable for all vehicle makes/models. This information was used to randomly select both the matched sample where systems were active as well as matching control samples where both of the L2 systems were available but inactive. Matched samples were not selected in instances when both of the L2 systems were unavailable, as the periods of time when L2 systems were unavailable may have contained different roadway environments and/or vehicle speeds not comparable to the sample of matched cases when systems were active.

To identify all of the matched samples, the matched case samples where L2 systems were active were identified first. Then, the control samples during which both L2 systems were available but inactive were identified, based upon the matching criteria listed below.

- Driver ID
- TOD (5 a.m.–7:59 a.m., 8 a.m.–11:59 a.m., 12 p.m.–3:59 p.m., 4 p.m.–6:59 p.m., 7 p.m.–9:59 p.m., 10 p.m.–12:59 a.m., 1 a.m.–4:59 a.m.)
- Day of week (weekday versus weekend)
- Vehicle speed (± 5 mph, with a minimum threshold vehicle speed of 20 mph)
- Phase of exposure (Phase 1, Phase 2, and Phase 3)

Sampling for Experienced L2 Drivers (VCC50 Elite NDS)

Because experienced L2 drivers in the VCC50 Elite NDS had owned their vehicles for at least 3 months, differences in behavior over time for this dataset were not examined. The L2 system state information is available in this dataset due to previously performed post-processing of a video image of the instrument panel. A machine-vision algorithm was developed to assess L2 system state using this image for 40 of the 50 vehicles instrumented in VCC50 Elite. Ten of the vehicles had an instrument panel display that did not permit the machine vision algorithm to be accurately trained to assess either L1 or L2 system state. Only 33 of these 40 included vehicles had L2 capabilities; thus, only data collected from those 33 vehicles were used in this analysis. There were 500 matched samples identified in this dataset with L2 systems active. The number of matched samples per driver was stratified based upon hours driven with L2 systems active.

Once segments with exposure to L2 systems were sampled, an additional 500 matched control samples were selected when L2 systems were available but inactive. These matched control samples were identified in the data stream using the same matching criteria as were used for the L2 NDS matched sampling.

Data Coding

For all matched samples for both experienced and inexperienced L2 drivers, trained data coders (Figure 2) used the recorded video, audio, and parametric data to reduce the driver, vehicle, and environmental factors that existed during each of the matched samples. The annotated data was then used to describe the circumstances observed in each matched sample. The research team followed current data coding protocols that were used for previous L2 NDS matched sample coding.

Figure 2. Data coding

Data coding also included an assessment of what behaviors were exhibited during each matched sample, including non-driving task engagement, evidence of drowsiness or non-secondary task impairment, and other aspects that might help characterize driver interaction with the L2 systems (e.g., misuse and abuse, such as using the L2 systems in adverse weather or circumventing the need to hold the steering wheel). A 15-second eye-glance coding protocol was performed on all matched samples to characterize the degree to which drivers monitored the road.

The environmental variables (Table 5) identified from the video included an assessment of

- roadway type,
- traffic density,
- relation to junction,
- weather conditions, and
- lighting conditions.

All coding took place in a secure data coding lab. To minimize vigilance decrements, coders were limited to short shifts and mandatory periodic breaks. To prevent video of drivers from being released to the public, all computers' external ports are inactive and mobile phones are prohibited in the data coding lab. These and all other procedures were approved by the Virginia Tech Institutional Review Board (IRB; Protocol #19-549).

Table 5. Variables Coded for Each of the Matched Samples (Cases and Controls) for Experienced and Inexperienced L2 Drivers (VCC50 Elite NDS; L2 NDS)

Category	Definition	Examples
Vehicle Variables	All of the descriptive variables, including the vehicle identifier (internal code), vehicle type, ownership, and those variables collected specifically for that vehicle, such as vehicle miles traveled.	Vehicle ID, vehicle type, L2 systems status, hours traveled
Environmental Variables	General description of the immediate environment, roadway, and any other vehicle during the last 5 seconds of the 15-second control segment.	GPS, weather, ambient lighting, road type, traffic density, relation to junction, surface condition, traffic flow, etc.
Secondary Task Engagement	Record of whether driver was active in a secondary task at any time during the 15-second epoch. Secondary tasks were recorded as specific tasks and up to six different secondary tasks were recorded.	Texting on mobile phone, talking on mobile phone, eating, applying makeup, talking with passenger, etc.
Driver's State	Description of the instrumented vehicle driver's physical state.	Hands on wheel, seat belt usage, fault assignment, drowsiness, eye-glance, etc.
Narrative	Written description of the entire event.	

Note: These same variables were the variables coded as part of the original data coding effort for inexperienced L2 drivers (L2 NDS).

Eye-Glance Behaviors

Off-road glance measures have been described above; however, each glance measure and acronym are more precisely described in Table 6. A detailed description of the on- and off-road glance locations used in this study can be found in Appendix B. Generally, "eyes-off-road" incidents were operationally defined as any glance location that would have no information critical to the task of driving. Those locations operationally defined as "on-road" would be locations that are critical to the driving tasks, including glances toward the windshield, mirror glances, or instrument cluster.

Table 6. Eye-Glance Measures

Glance Measure	Description
Total Eyes-Off-Road Time	The summation of all glance durations to all areas of interest other than the road scene ahead during a sample interval in seconds (SAE International, J941_201003, 2016, 2017).
Mean Off-road Glance Duration	The average duration of all glances away from the road scene during the 15-second sample interval.
Single Longest Off-road Glance	The duration of the single longest glance away from the road scene during the sample interval.
Number of Off-road Glances	The number of glances away from the road scene during the 15-second sample interval.

Secondary Task Engagement

The method of task classification is described below in Table 7, where each secondary task was grouped by either task type or risk level. The levels of high risk were based upon odds ratio calculations in Dingus et al. (2016) where driver secondary task prevalence and each type of task's contribution to crash risk were assessed using data from the SHRP 2 NDS. Thus, high risk secondary tasks were those that increased crash risk in the Dingus et al. analysis. The levels of low risk were found to not increase crash risk in the Dingus et al. analysis. In the present analysis, up to six secondary task behaviors were coded within each 15-second epoch. The prevalence of secondary tasks was compared between events in which L2 systems were active versus those in which L2 systems were inactive.

Table 7. Secondary Task Classification

Secondary Task	Task Type	Risk Level	Disaggregate Tasks
Any Task	N/A	N/A	If secondary task 1 was populated with a task other than "No Secondary Task"
All Mobile Phone			All mobile phone tasks
Visual-Manual Mobile Phone	Visual-Manual	High	All mobile phone tasks excluding talking
Talking	Cognitive	Low	Mobile phone, talking/listening, handheld
Texting	Visual-Manual	High	Mobile phone, texting
Dialing			Mobile phone, dialing handheld including using quick keys
Browsing			Mobile phone, browsing
Reaching Phone			Mobile phone, locating/reaching/answering
Reaching for Object in Vehicle (non-mobile phone)			Reaching for cigar/cigarette
			Reaching for food-related or drink-related item
			Interaction with moving object
			Reaching for object, other
			Tablet device, locating/reaching
			Reaching for personal body-related item
External Distraction			Looking at an object external to the vehicle

Secondary Task	Task Type	Risk Level	Disaggregate Tasks
			Looking at previous crash or incident
			Looking at pedestrian
			Looking at animal
			Other external distraction
Passenger Interaction (adult or child)	Cognitive	Low	Passenger in adjacent seat – interaction
			Passenger in rear seat – interaction
			Child in adjacent seat – interaction
			Child in rear seat – interaction
Hygiene	Visual-Manual		Biting nails/cuticles
			Combing/brushing/ fixing hair
			Removing/inserting/ adjusting contact lenses or glasses
			Other personal hygiene
			Applying make-up
			Brushing/flossing teeth
			Removing/adjusting clothing
			Removing/adjusting jewelry
Drinking (non-alcohol)	Manual		Drinking with lid, no straw
			Drinking with lid and straw
			Drinking with straw, no lid
			Drinking from open container
Eating	Visual-Manual		Eating without utensils
			Eating with utensils
Reading/Writing (includes tablet)		High	Reading
			Writing
			Tablet device, viewing
			Tablet device, other
			Tablet device, operating
Dancing	Manual	Low	Dancing

Results

The following exploratory analyses were conducted to evaluate how drivers' strategies and behaviors may change after their initial introduction to L2 systems. This analysis covered driver behaviors while using L2 systems, the conditions in which drivers chose to engage L2 systems, and general exposure of L2 system use. Typically, the analyses compared specific driver behaviors or general exposure by L2 system state: L2 systems active versus L2 systems available but inactive. Descriptive statistics (e.g., mean, maximum, standard deviation), histograms, and cumulative step graphs of the data were used to examine distributions prior to conducting statistical analyses to determine if there were any outliers or other anomalies that might need to be accounted for in the analysis. No outliers were identified in this process.

To evaluate contributing factors for binary outcome variables (for example, high-risk secondary task engagement in which there is either presence of a secondary task or no presence), logistic regression was employed. When the outcome variables were continuous, such as the duration of eyes-off-road time, or number of mph over the speed limit, a linear regression or analysis of variance (ANOVA) was used. When the outcome variables were integers, such as the number of eye glances away from the road or toward the instrument cluster, a Poisson model was developed. For frequency metrics, chi-square tests were used.

For this study, each participant could have more than one observation (Figure 3), which may have resulted in subject-specific effects. This effect was included as a random effect in all of this study's regression models (the analyses controlled for the effect of the individual driver). Interaction terms such as exposure phase and L2 activation were included when interaction effects may have existed, as based on exploratory analysis and subject expertise.

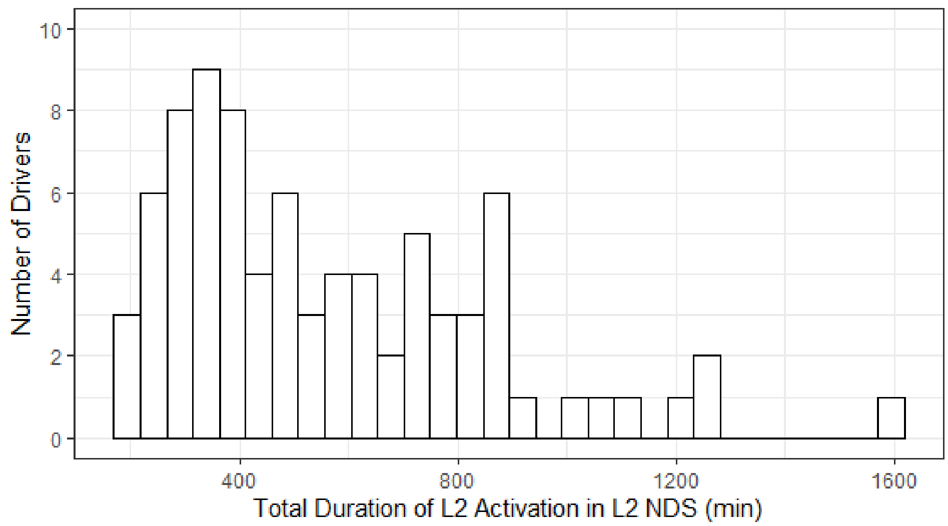


Figure 3. Distribution of the number of drivers by their cumulative L2 activation (in minutes)

Due to the interest in exposure to L2 systems over time, it became apparent that participants who had longer driving exposure to L2 also generally drove more than those drivers who did not have a lengthy exposure to L2 systems. Thus, two groups of drivers (Shorter L2 Activation and Longer L2 Activation) were created for inexperienced L2 drivers in the L2 NDS dataset. These were operationally defined as drivers who had L2 activation time greater than 8 hours (Longer L2 Activation group) and drivers who had less than 8 hours of L2 activation (Shorter L2 Activation group).

Some important differences were identified for those drivers with Longer L2 Activation versus those with Shorter L2 Activation. First, those drivers who drove with L2 systems active for greater than 8 total hours also appeared to drive with L2 systems more frequently in the first few days of data collection compared to those drivers who accumulated less than 8 hours of L2 system activation. Figure 4 shows that the time to complete 3 hours of L2 system activation was shorter (mean = 7.3 days) for the drivers who accumulated greater than 8 hours of L2 system activation and longer (mean =13.2 days) for the drivers who accumulated less than 8 hours of L2 system activation over the duration of the study. Due to this dramatic difference between these two groups of drivers, key analyses included L2 activation group as a variable in the statistical model to ensure that any significant results were not an artifact of the differences in either total overall driving time with L2 systems active or other unknown systematic differences that may exist between these two groups of drivers.

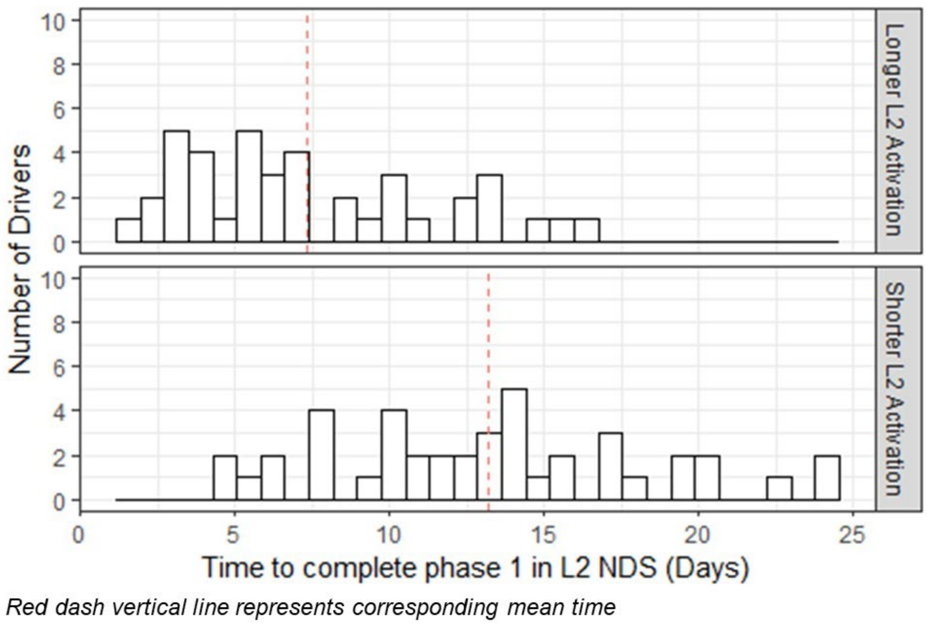


Figure 4. Distribution of percentage of drivers by the number of days to accumulate 180 hours of driving with L2 systems active

The results section below is organized by each research objective:

- How do driver strategies and behaviors for maintaining vehicle safety using L2 systems change over time?
- What factors influence how drivers rely on, and adapt to, these L2 systems?
- What are the relevant outcomes of adaptation and reliance upon these L2 systems?
- What are the lessons learned from drivers using these L2 systems?

Objective 1: How do driver strategies and behaviors for maintaining vehicle safety using L2 Systems change over time?

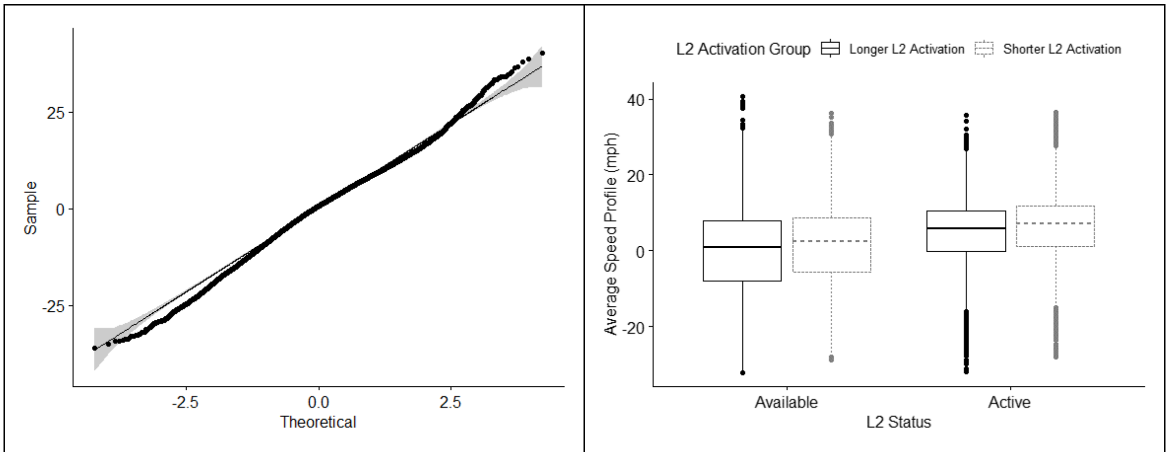
Driver Strategies

Speed Selection

1. Do drivers tend to select higher speeds (in relation to the speed limit) when initiating L2 systems compared to driving when L2 systems are available but inactive?

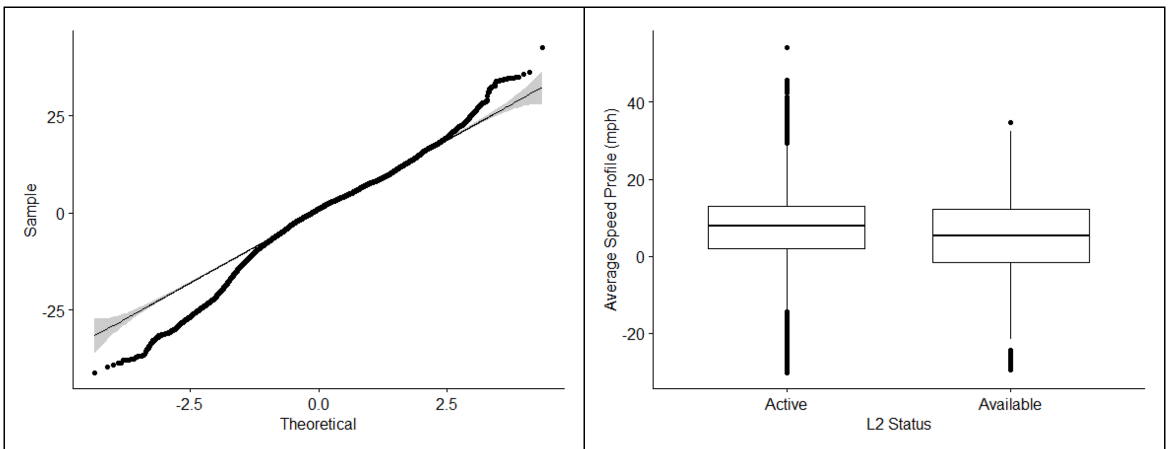
The following analyses used data on the activation of L2 systems and data from the matched samples to assess the speed that drivers were traveling as they activated the L2 systems compared to when they were not using L2 systems. For the analyses that used the activation of L2 systems and the matched sample, ANOVA procedures were used to assess whether significant differences existed between groups. While ANOVA is a robust test, we included subjects as a random effect variable to ensure that we maintained the assumption of independence. The results below (Figure 5a and Figure 6a) are from a mixed-effect linear regression model that uses a participant-specific random effect terms to accommodate the participant-level correlation. We also conducted tests for normality and homogeneity of variance for inexperienced L2 drivers (L2 NDS) in Figure 6a and for experienced L2 drivers (VCC50

Elite NDS) in Figure 6b below. These show that the normality and equal variance assumption are not violated.



a) QQ plot: residual check   b) Equal variance check

Figure 5. QQ plot and box plot of inexperienced L2 drivers (L2 NDS)



a) QQ plot: residual check   b) Equal variance check

Figure 6. QQ plot and box plot of experienced L2 drivers (VCC50 Elite NDS)

The speed distributions are plotted below in Figure 7 and Figure 8, in which the x-axes indicate speed in relation to the speed limit. Thus, 0 in the center of the x-axis refers to the vehicle traveling at the same speed as the posted speed limit (no difference in GPS speed and the posted speed limit). The y-axis represents the proportion of activations that occurred within each speed bin. Data plotted to the left of 0 indicates that the vehicle speed was slower than the posted speed limit. Data plotted to the right of 0 indicates that the vehicle speed was faster than the posted speed limit.

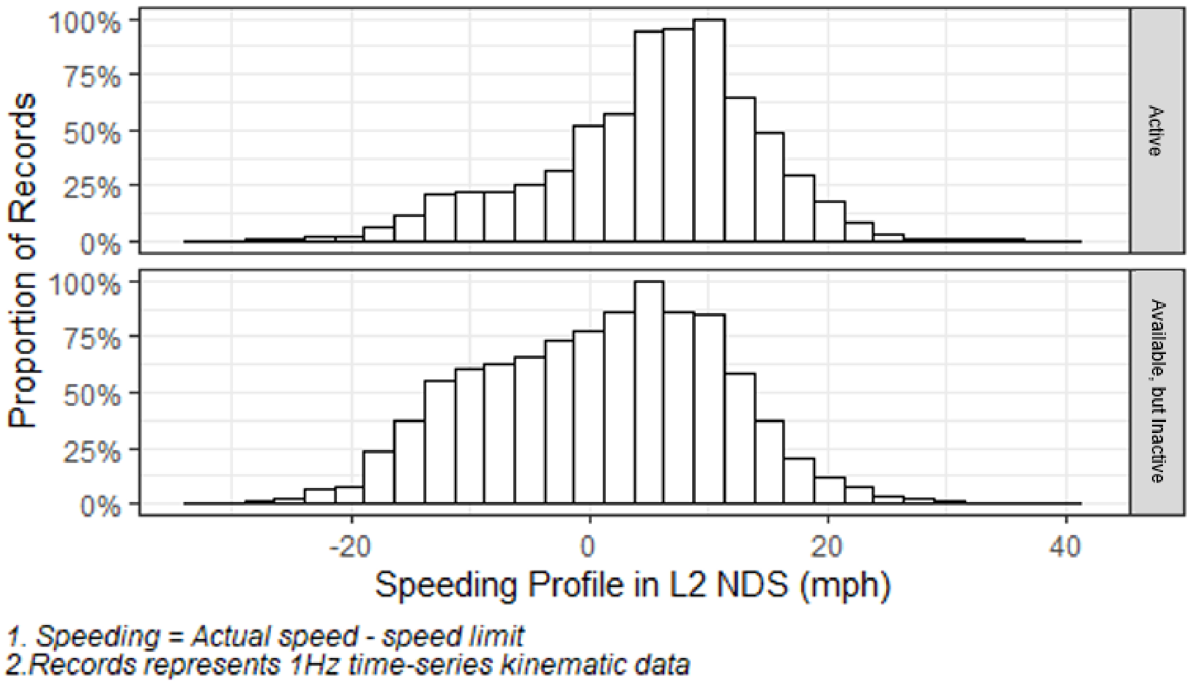


Figure 7. Inexperienced L2 (L2 NDS) driver speed selection profiles for when L2 systems were active (top) compared to L2 systems were available but inactive (bottom)

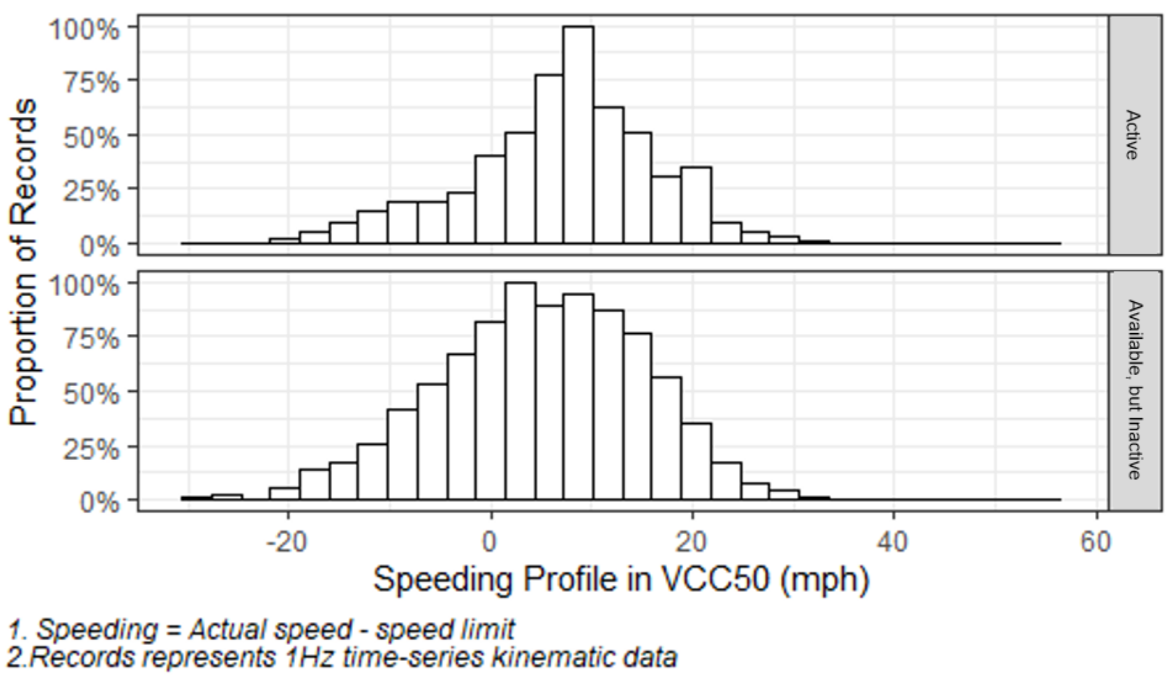


Figure 8. Experienced L2 driver (VCC50 Elite) speed selection profiles for when L2 systems are active (top) compared to when L2 systems are available but inactive (bottom)

Note that for inexperienced L2 drivers in the L2 NDS, there are two categorical variables: L2 status and L2 driver activation group; the interaction between them is also explored as shown in Figure 9 below. Two parallel lines imply that there are less likely to be interaction effects between these two variables. The mixed-effect linear regression model also confirmed that the interaction term is not significant ($F(1, 42{,}707) = 1.51$, $p = .22$). Therefore, only two main effects were kept in the final model for inexperienced L2 drivers (L2 NDS).

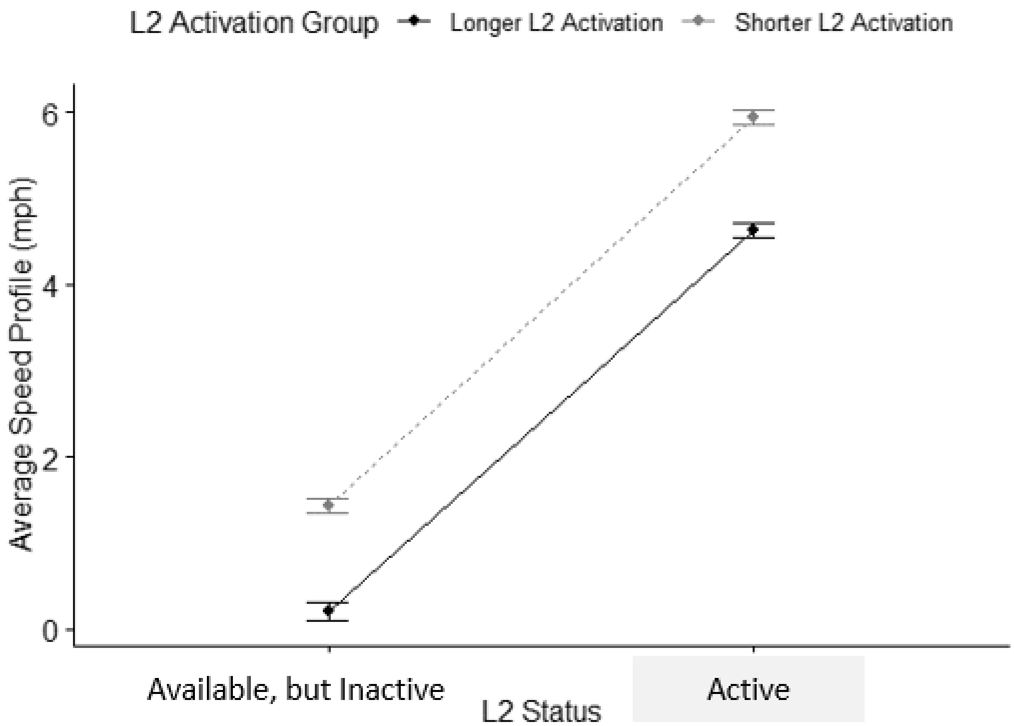


Figure 9. Interaction between L2 Status and L2 Activation Group for Inexperienced L2 Drivers (L2 NDS)

Both inexperienced L2 drivers (L2 NDS) and experienced L2 drivers (VCC50 Elite NDS) tended to select speeds above the speed limit more frequently when L2 systems were active than when L2 systems were available but inactive ($F(1,42{,}405) = 2724.83$, $p < .001$ for inexperienced L2 drivers; and $F(1,75{,}208) = 452.12$, $p < .001$ for experienced L2 drivers). On average, drivers tended to travel 4.56 mph higher for inexperienced L2 drivers and 2.66 mph higher for experienced L2 drivers when L2 systems were active than when L2 systems were available but inactive. The random effect from participants is 13.09 and 17.14 while the standard deviation is 80.17 and 71.68 for the inexperienced L2 drivers and experienced L2 drivers respectively, which implies that the mixed-effect linear model outperforms the regular linear model.

2. Do drivers tend to select speeds higher than the speed limit more frequently during the first three hours of exposure (Phase 1) to L2 systems compared to longer cumulative exposure (Phase 2 and Phase 3) to L2 systems?

To answer this research question, it was important to control the analysis for those participants who accumulated more time with L2 systems active versus those who accumulated less time with systems active. Figure 10 shows the speed selection profiles of the drivers with shorter L2 activation (top row) versus those drivers with longer L2 activation (bottom row). The left side of the figure is the speed selection profile when L2 systems were active, and the right side of the figure is the speed selection profile for the matched sample when L2 systems were available but inactive. The mixed-effect linear regression model shows that these two driver groups were significantly different in that the drivers with less L2 activation selected higher speeds more frequently than drivers with longer L2 activation, $F(1,77) = 4.38$, $p = .04$. Hence, a stratified analysis was conducted to further explore speed selection within each L2 activation group.

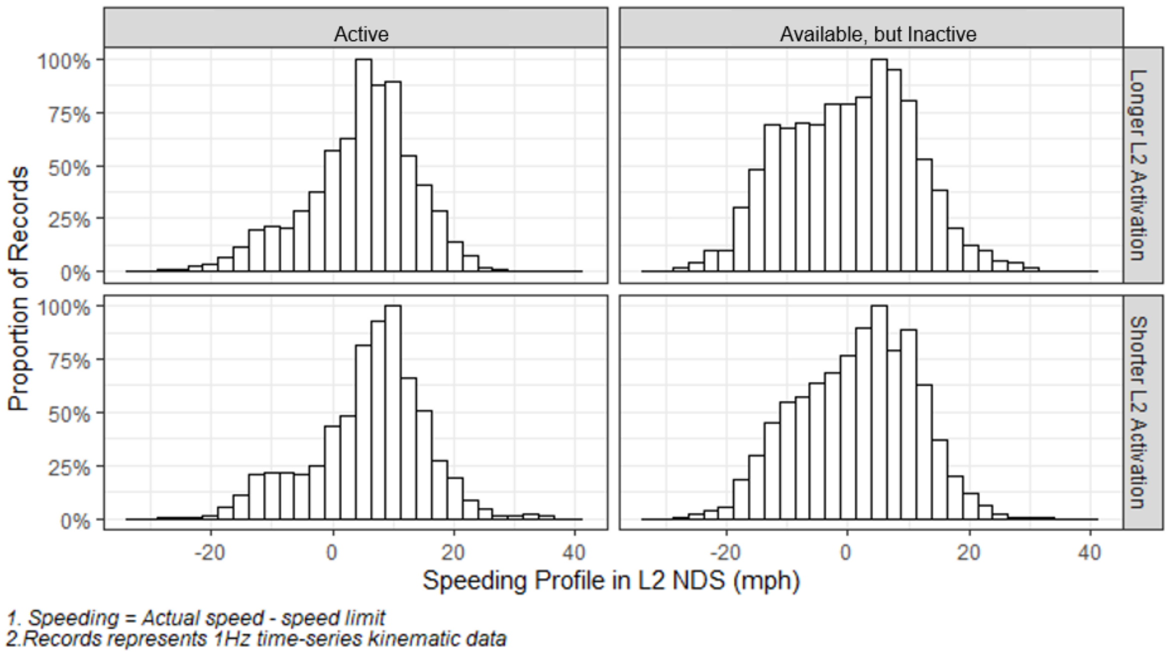


Figure 10. Inexperienced L2 (L2 NDS) driver speed selection profiles by L2 system status for each L2 activation group

To assess speed selection over time, the analysis was again split by the L2 Activation groups. The analysis indicated that there were significant main effects for L2 status, $F(1, 23{,}145) =1{,}483.83$, $p < .001$) and phase, $F(1, 23{,}160) =53.45$, $p < .001$). Figure 11 shows the speed selection profile for drivers with shorter L2 activation time. The top row represents Phase 1, and the bottom row represents Phase 2. These drivers increased their frequency of selecting higher speeds over time when L2 systems were active as well as when the systems were available but inactive. Drivers also more frequently selected higher speeds when L2 systems were active than when L2 systems were available but inactive.

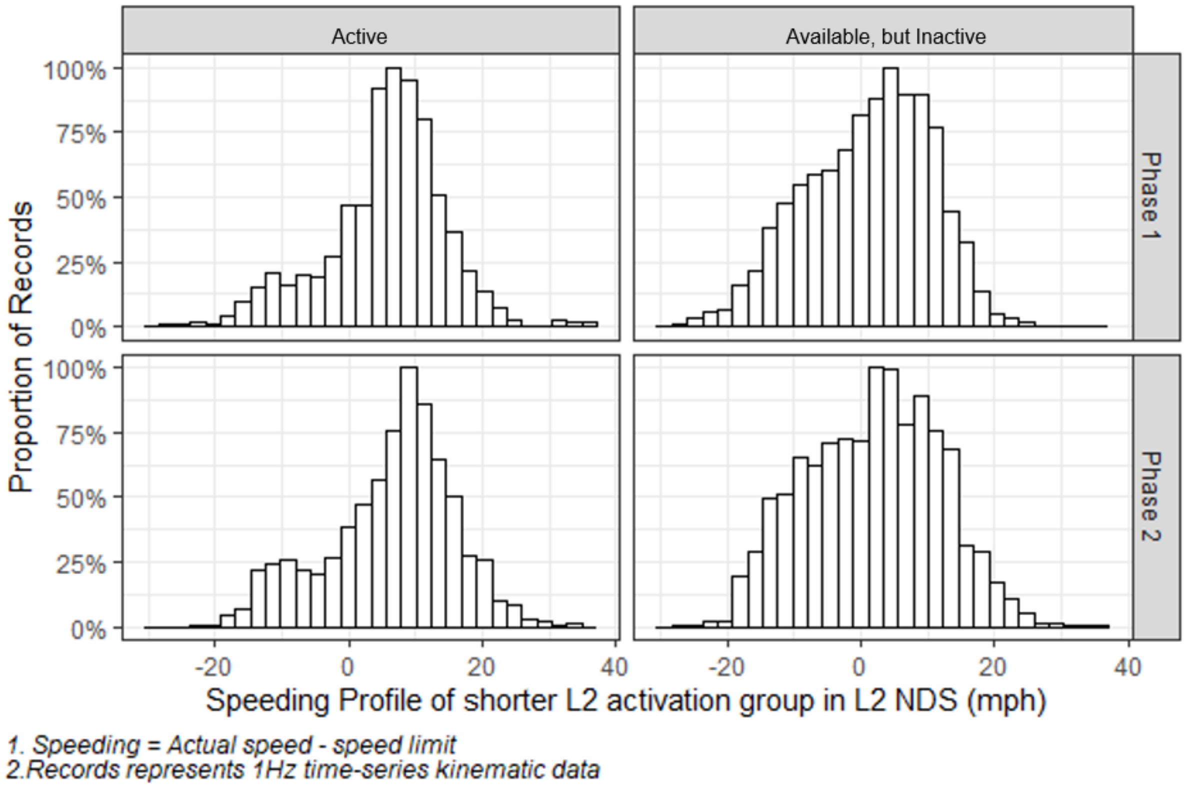


Figure 11. Speed selection profiles for drivers who had shorter L2 system activation at each exposure phase and L2 status

A different pattern was found for those drivers with longer L2 activation. Again, the model analysis indicates that the main effect of L2 status was significantly different, $F(1, 19{,}259) = 1{,}244.44$, $p < .001$, indicating that drivers tended to select faster speeds more frequently when L2 systems were active than when they were available but inactive. There was not a main effect of Exposure Phase for this group (i.e., no difference in speed selection over time). However, there was an interaction effect on speed selection profiles between Exposure Phase and L2 status, $F(2, 19{,}255) = 10.01$, $p < .001$. Figure 12 shows similar speed selection profiles where the top row represents Phase 1, the middle row represents Phase 2, and the bottom row represents Phase 3. The left column represents when L2 systems were active, and the right column represents when L2 systems were available but inactive.

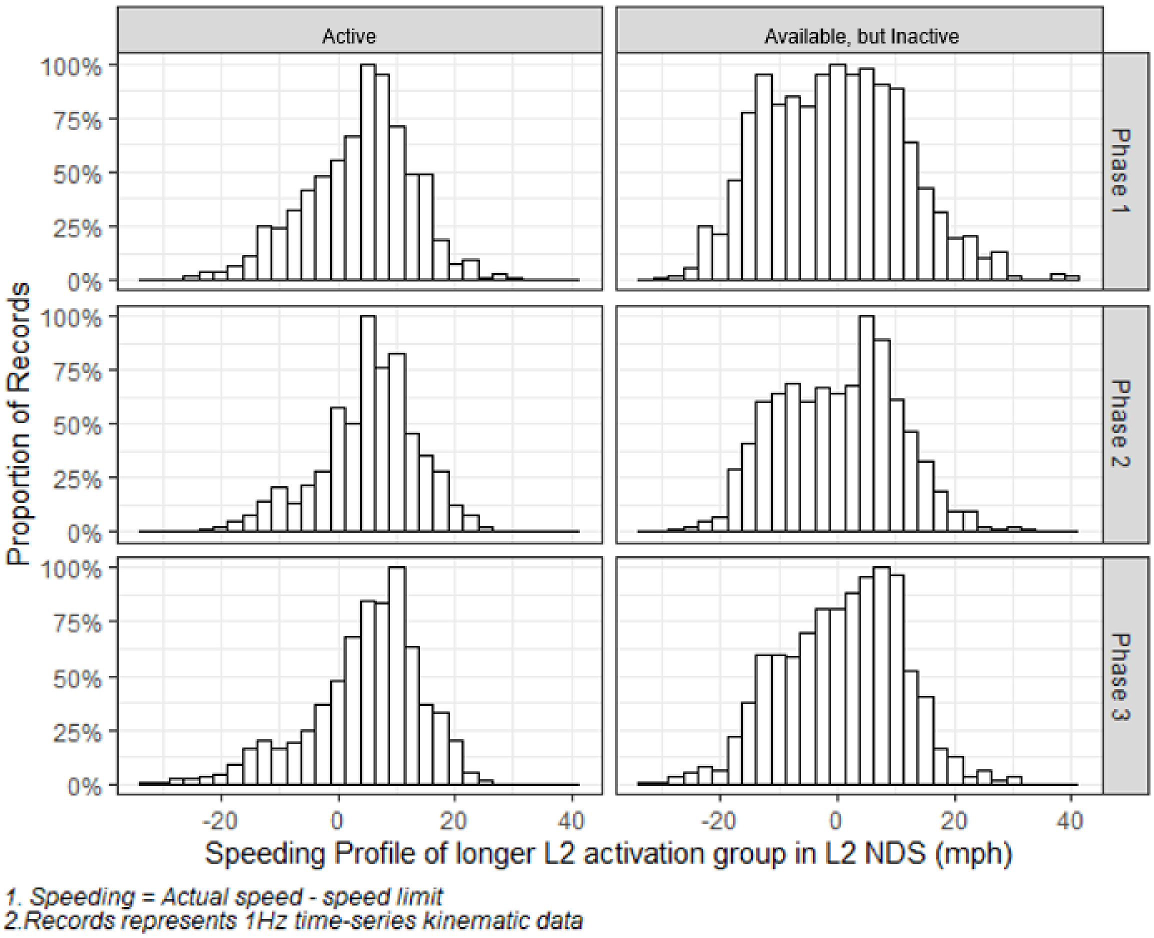


Figure 12. The speed selection profiles for the drivers who had longer L2 system activation at each exposure phase and L2 status

Driver Behavior

Glance Away From the Forward Roadway

Do drivers look away from the roadway longer while using their L2 systems? How does this vary by exposure phase?

Inexperienced L2 Driver (L2 NDS) Analysis

Glance metrics were calculated using the matched sample datasets for both inexperienced L2 drivers (L2 NDS) and experienced L2 drivers (VCC50 Elite NDS). Driver glance behavior was assessed by L2 system status and L2 exposure phase for inexperienced drivers. Exploratory analyses were conducted to assess the frequency of any glance off the forward roadway by matched sample, which includes both the case sample with L2 active as well as the matched control sample with L2 available but inactive. Figure 13 shows the histogram of matched samples by total eyes-off-road duration (seconds). Over half the matched samples had no eyes-off-road time. A mixed-effects Poisson regression was used to assess significant differences in eyes-off-road count by L2 status and exposure phase with participants used as a random effect variable. The results indicated a significant main effect for L2 status in that participants were looking away in more matched samples when L2 systems were active than when L2 systems were available but inactive. Additionally, there was a main effect of phase in that drivers looked away more often in Phase 3 than in Phase 1, but there was no significant difference between Phase 2 and Phase 1, or between Phase 3 and Phase 2 (see Poisson test results in Table 8).

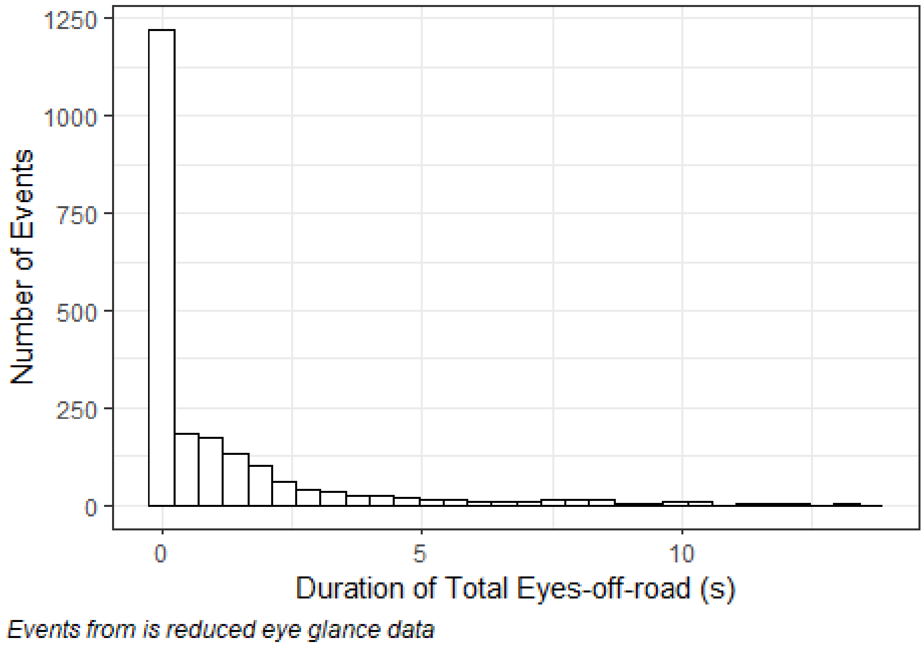
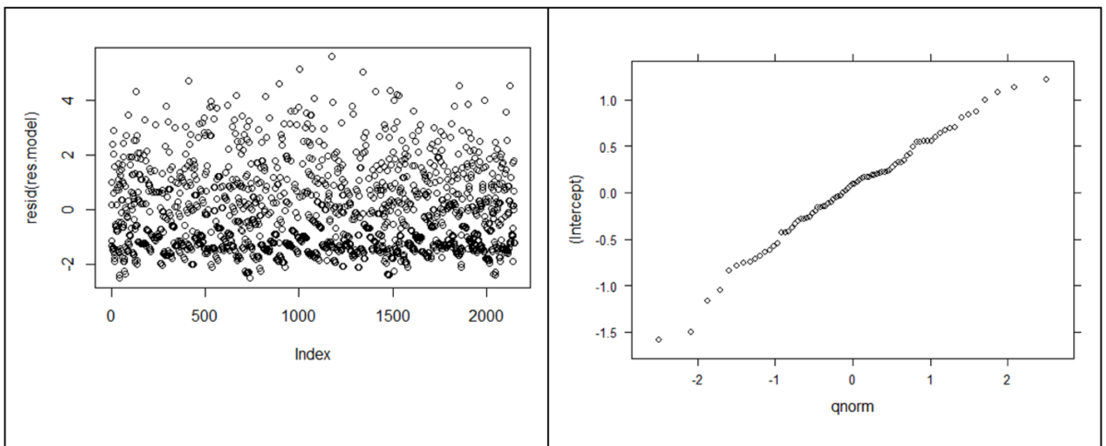


Figure 13. Histogram of matched samples by duration of total eyes-off-road time

A residual and mixed-effect of Poisson regression model was checked, as shown in Figure 14 below. The residual plot shows a symmetrical distribution around 0 and no clear patterns, and the QQ plot meets the normality assumption. The value of Akaike information criterion (AIC) is 7140.9 for the model.



a) Residual plot

b) QQ plot

Figure 14. Random effect check for mixed-effect Poisson model for inexperienced L2 drivers (L2 NDS, eyes-off-road)

Table 8. Results of the Mixed-Effect Poisson Regression Comparing Eyes-Off-Road Glance Behavior by L2 Status and Exposure Phase

	Estimated Coefficient	**Standard Error**	***Z* value**	***p***
Intercept	-0.065	0.081	-0.81	.42
L2 Status (Available but inactive versus Active)	-0.09	-0.04	-2.24	.025
Phase 2 versus Phase 1	0.08	0.05	1.83	.07
Phase 3 versus Phase 1	0.167	0.07	2.55	.011
Phase 3 versus Phase 2	0.079	0.068	1.16	.246

Given that drivers were more likely to look off the forward roadway when L2 systems were active, the rest of the analyses will focus on those matched samples where drivers looked away from the forward roadway. An ANOVA was conducted to assess whether eyes-off-road glance metrics were significantly longer when L2 systems were active versus available but inactive and if eye-glance durations changed over time. Four glance metrics, the total eyes-off-road time, the mean duration of glances, the single longest glance, and the number of glances were computed for eyes-off-road (Figure 15) as were metrics for eyes on the instrument cluster (Figure 16).

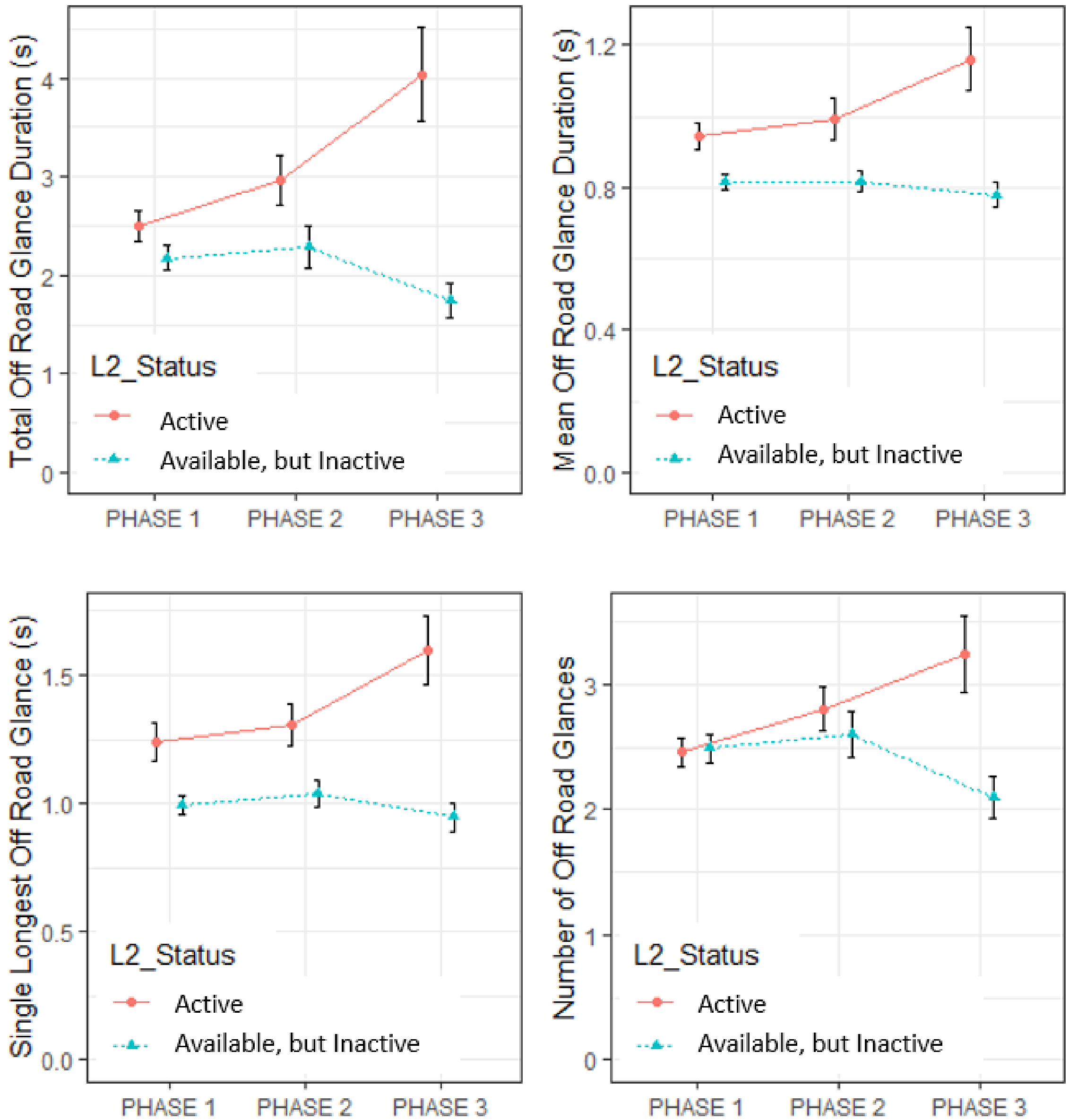


Figure 15. Total eyes-off-road time (top left), mean glance off-road duration (top right), single longest off-road glance (bottom left), and number of off-road glances (bottom right), for each adaptation phase for the inexperienced L2 drivers (L2 NDS)

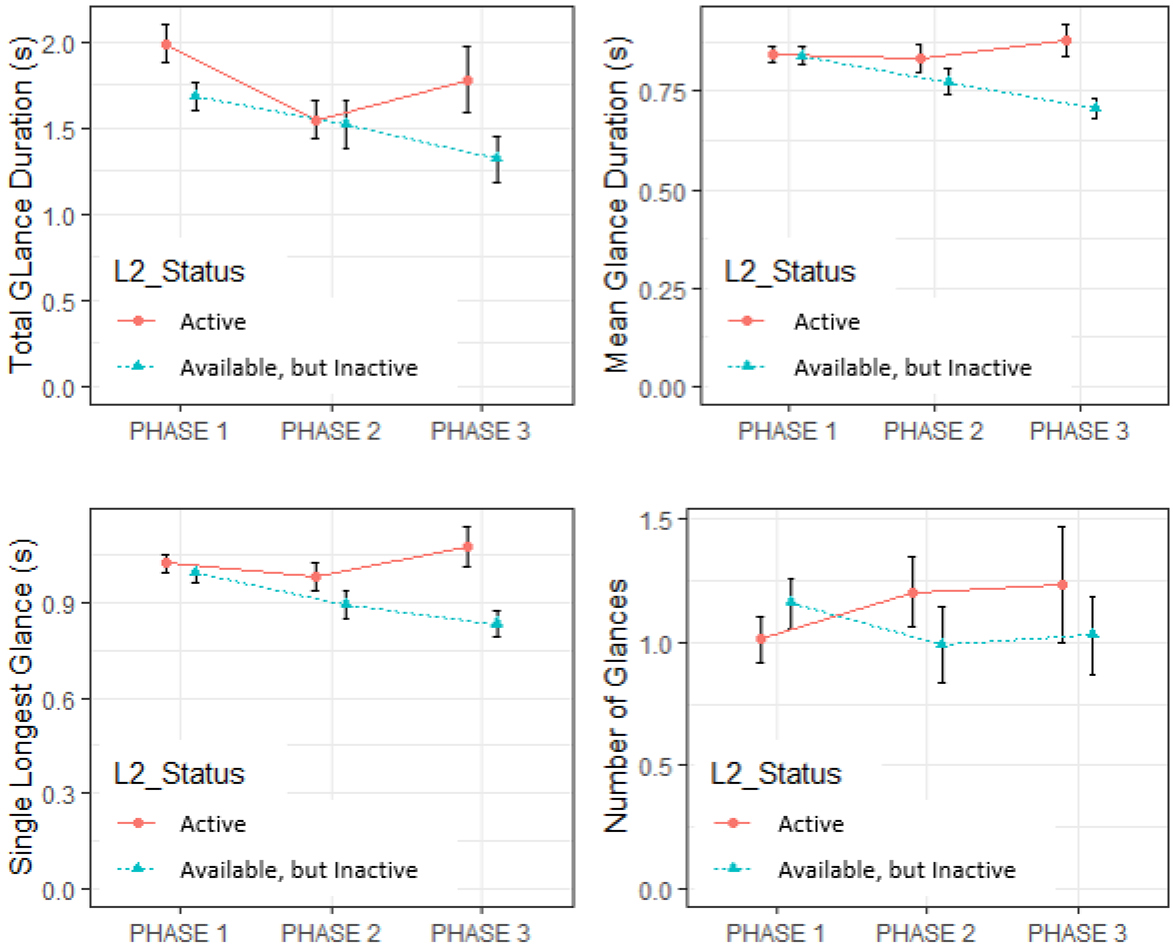


Figure 16. Total glance duration (top left), mean glance duration (top right), single longest glance to instrument panel (bottom left), and number of glances to the instrument panel (bottom right), for each exposure phase for inexperienced L2 drivers (L2 NDS)

The normality assumption checks are shown in Figure 17. The results indicate that drivers looked away from the forward roadway significantly longer when L2 was active versus when L2 was available but inactive for total glance duration, $F(1, 934) = 19.30$, $p < .001$); mean glance duration, $F(1, 934) = 29.67$, $p < .001$; and single longest glance, $F(1, 934) = 31.28$, $p < .001$. The numbers of glances were not statistically different from each other ($F(1,934) = 3.03$, p = p = .082). While the main effect of phase was not significant (total glance duration, $F(2, 934) = 2.38$, $p = .09$; mean glance duration, $F(2, 934) = 1.41$, $p = .24$; single longest glance, $F(2, 934) = 1.49$, $p = .22$; and number of glances, $F(2, 934) = 1.21$, $p = .29$), the interaction of L2 status by phase was significant, where glance duration off road increased across phase when L2 systems were active but not when available but inactive. This result was found for total glance duration, $F(2, 934) = 8.65$, $p < .001$; mean glance duration, $F(2, 934) = 3.51$, $p = .03$; single longest glance, $F(2, 934) = 2.36$, $p = .04$; and number of glances, $F(2, 934) = 5.14$, $p = .06$).

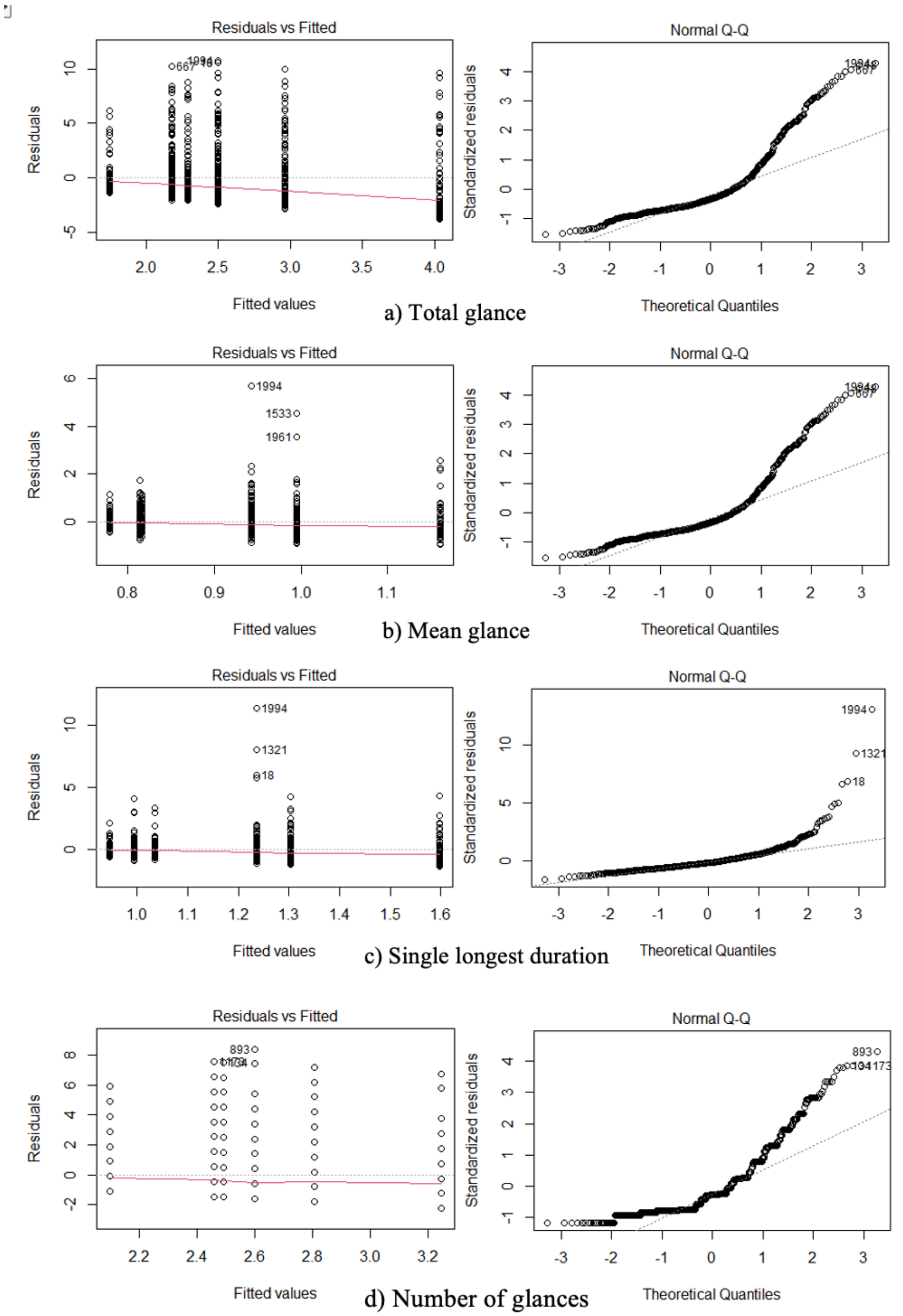


Figure 17. Assumption check for total eyes-off-road time (top left), mean glance off-road duration (top right), single longest off-road glance (bottom left), and number of off-road glances (bottom right), for each adaptation phase for the inexperienced L2 drivers (L2 NDS, eyes-off-road)

A similar analysis was conducted for eyes on the instrument cluster. Figure 18 shows the histogram of matched samples with glances toward the instrument cluster. A mixed-effect Poisson regression model indicated that drivers tended to look at the instrument cluster significantly more often when L2 systems were active than when available but inactive (see Table 9 for regression results). Additionally, the duration of eyes on instrument cluster was significantly longer in Phase 1 than in Phase 2 or Phase 3 (see Table 9).

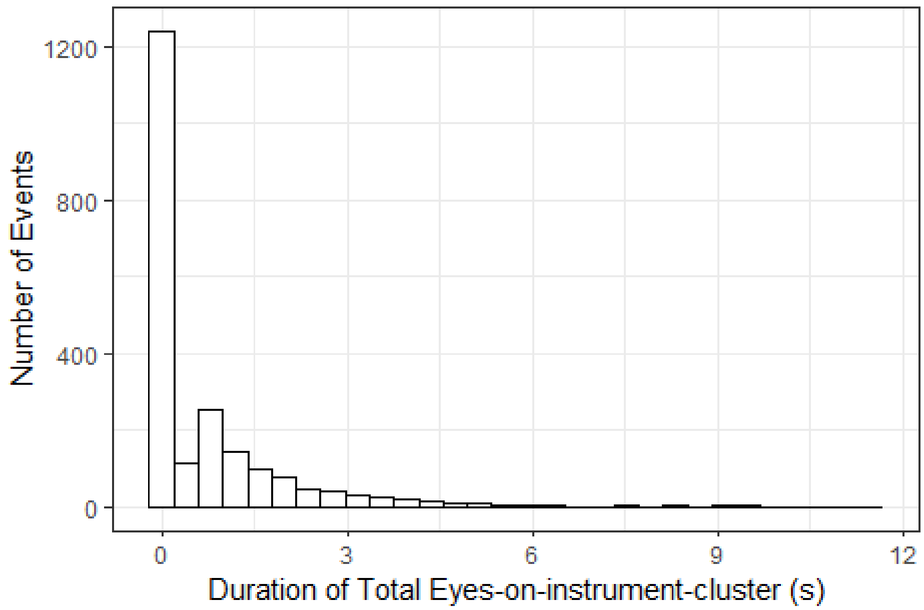
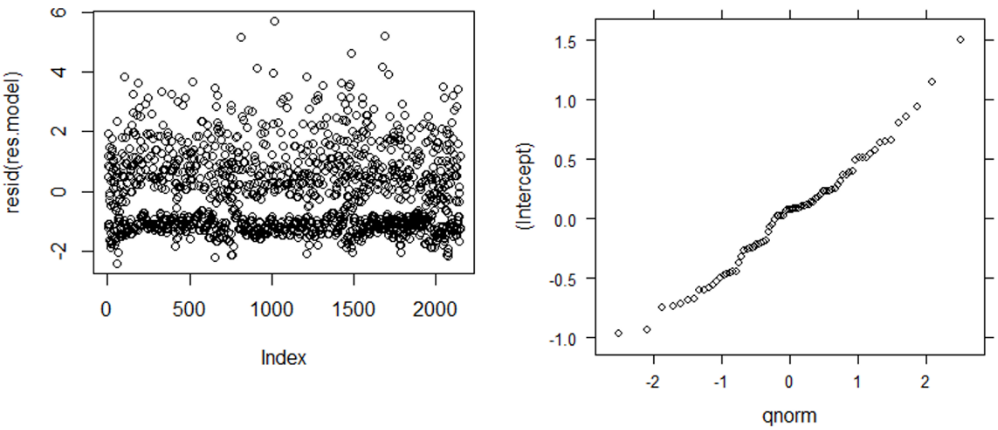


Figure 18. Histogram of matched samples by duration of total eyes-on-instrument-cluster time

Table 9. Results of the Mixed-Effect Poisson Regression Comparing Eyes on Instrument Cluster by L2 Status and Exposure Phase

	Estimated Coefficient	**Standard Error**	***Z* value**	***p***
Intercept	-0.074	0.073	-1.004	.32
L2 Status (Available but Inactive versus Active)	-0.23	-0.05	-4.92	< .001
Phase 2 versus Phase 1	-0.25	0.056	-4.47	< .001
Phase 3 versus Phase 1	-0.31	0.076	-4.05	< .001
Phase 3 versus Phase 2	-0.06	0.082	-0.69	.491

The assumption check for the mixed-effect Poisson model is shown in Figure 18.



a) Residual plot b) QQ plot

Figure 19. Random effect check for mixed-effect Poisson model for inexperienced L2 drivers (L2 NDS, eye on instrument cluster)

Using those matched samples where drivers glanced toward the instrument cluster (i.e., removing those matched samples with no glances towards the instrument cluster), an ANOVA was conducted to assess the impact of the L2 status and exposure phase (see Figure 20). The results indicated that drivers looked at the instrument cluster for longer durations of time when L2 systems were active than when they were available but inactive. This was true for total glance duration, $F(1, 907) = 6.20$, $p = .013$ and single longest glance duration, $F(1, 907) = 6.4$, $p = .012$.

Results were not statistically significant for the metric of mean glance duration, $F(1, 907) = 3.73$, $p = .054$; and number of glances, $F(1, 907) = 3.15$, $p = .076$. Additionally, when assessing total glance duration, a main effect for the exposure phase was also significant, where drivers looked at the instrument cluster longer during Phase 1 than during Phase 2, $F(1, 907) = 4.54$, $p = .011$. There were not significant differences between Phase 1 and Phase 3 ($p = .115$), and Phase 2 and Phase 3 ($p = .993$). The main effect of phase was not significant for mean glance duration ($F(2,907) = 1.72$, $p = .180$), single longest glance ($F(2,907) = 2.25$, $p = .105$), or number of glances ($F(2,907) = 2.91$, $p = .055$). Additionally, there was a significant interaction of L2 status and exposure phase, but only for mean glance duration, $F(2, 907) = 3.28$, $p = .038$ (total glance duration, $F(1, 907) = 1.06$, $p = .35$, single longest glance duration, $F(1, 907) = 2.64$, $p = .072$; and number of glances ($F(2,907) = 1.01$, $p = .363$). Here, mean glance duration did not change across phase when L2 was active but significantly decreased when L2 was available but inactive. No other glance metric had a significant interaction result.

The assumption checks for this ANOVA are shown in Figure 21.

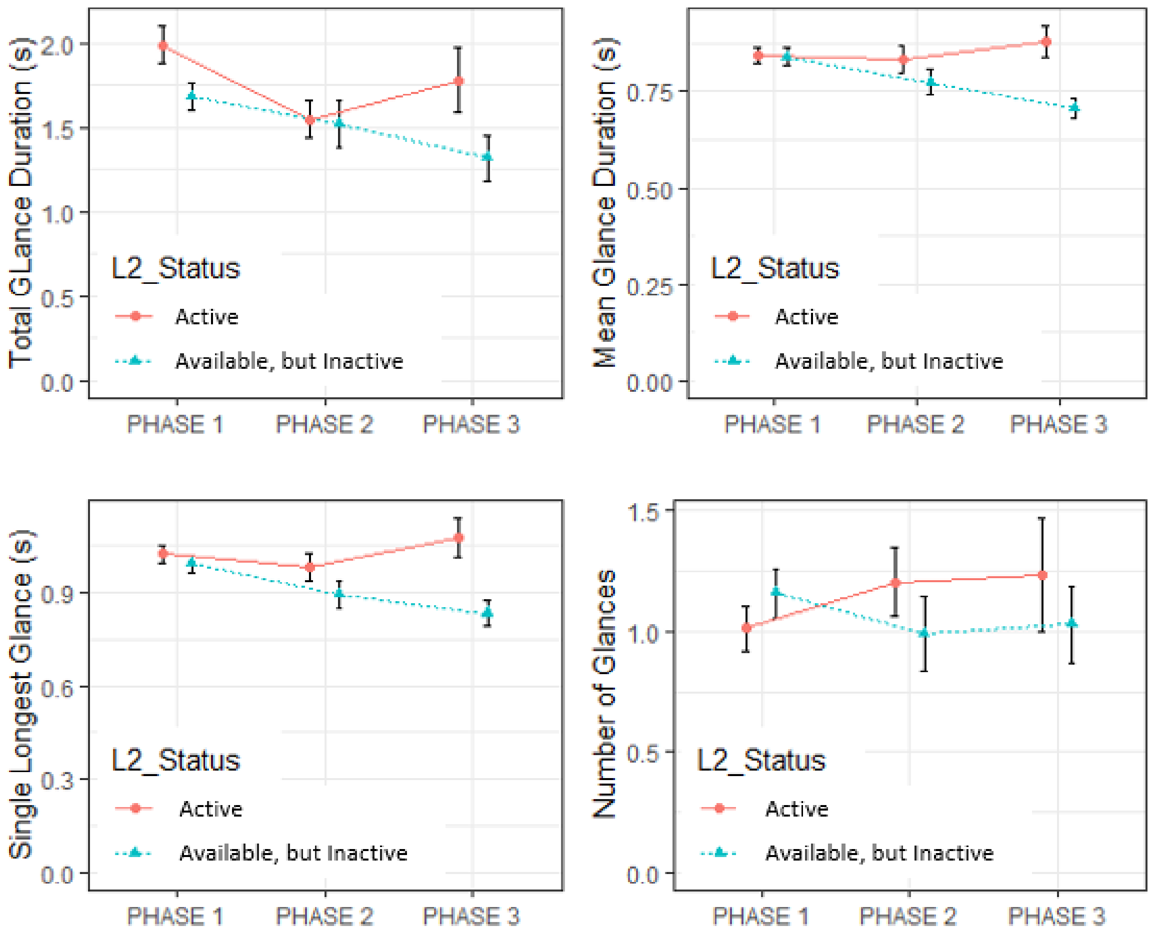


Figure 20. Total glance duration (top left), mean glance duration (top right), single longest glance to instrument panel (bottom left), and number of glances to the instrument panel (bottom right), for each exposure phase for inexperienced L2 drivers (L2 NDS)

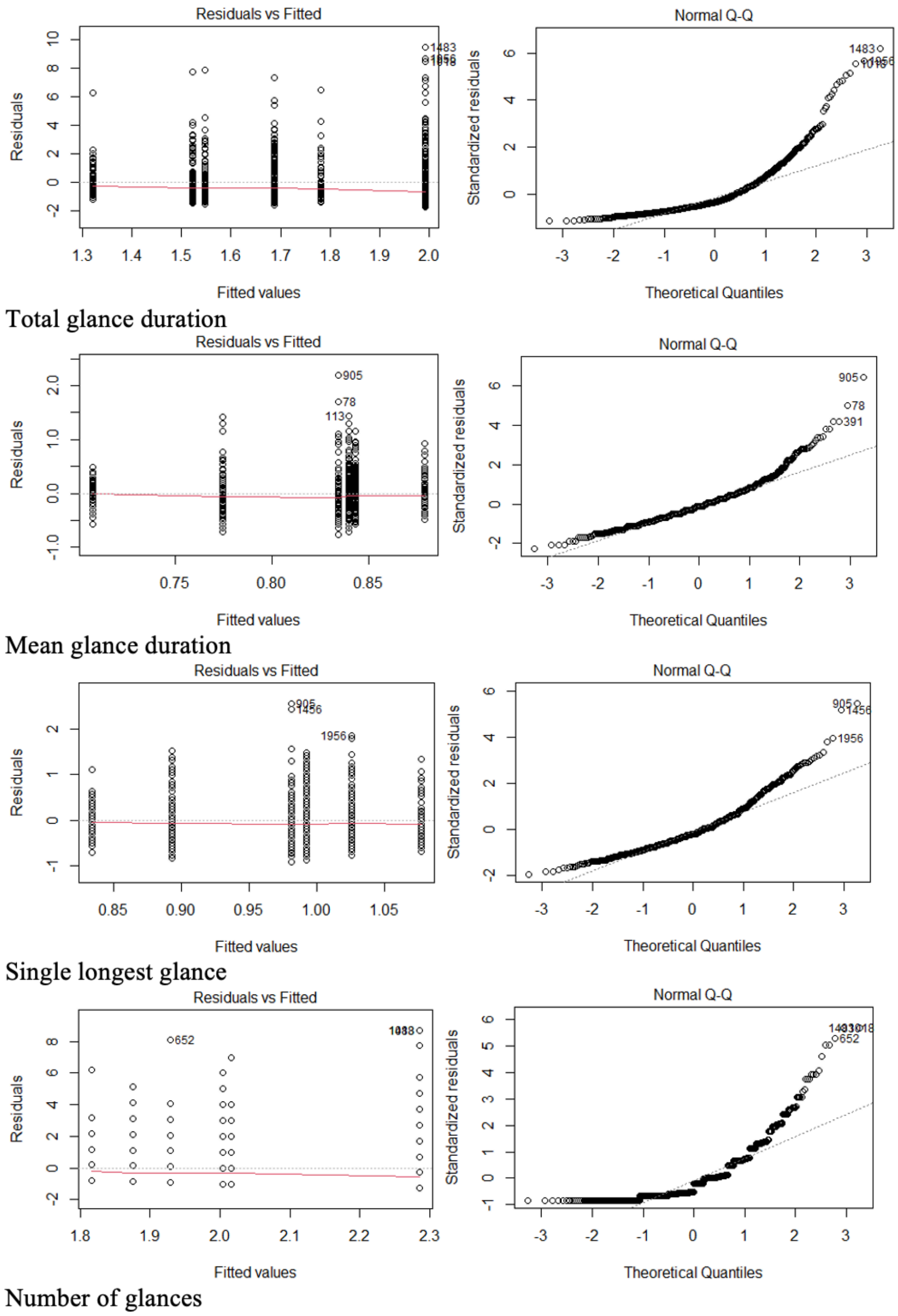


Figure 21. Assumption check for total eyes-off-road time (top left), mean glance off-road duration (top right), single longest off-road glance (bottom left), and number of off-road glances (bottom right), for each adaptation phase for the inexperienced L2 drivers (L2 NDS, Instrument Cluster)

Experienced L2 Drivers (VCC50 Elite) Glance Analysis

Glance metrics were calculated using the matched sample datasets for the experienced L2 drivers (VCC50 Elite NDS). Driver glance behavior was assessed by L2 system status for these drivers, as their behavior was not expected to change over time. Similarly non-zero eyes-off-road glances were compared between the two L2 system status conditions via ANOVA test. Figure 22 shows results which indicate that experienced drivers are similar to inexperienced drivers in that eyes-off-road time was significantly higher when L2 systems were active compared to when L2 systems were available but inactive. This was true for total eyes-off-road duration, $F(1, 465) = 17.72$, $p < .001$; mean glance duration, $F(1, 465) = 15.23$, $p < .001$; and single longest glance duration, $F(1, 465) = 23.37$, $p < .001$. There was no significant difference for the number of glances, $F(1, 465) = 2.35$, $p = .126$.

While direct comparisons between these two groups of drivers were not made due to differences in the two populations (i.e., driving their personal vehicle, significantly longer data collection period), eyes-off-road durations for all the metrics below are slightly higher than what was observed for the inexperienced drivers, especially when L2 systems were active.

The assumption checks for this ANOVA are shown in Figure 23.

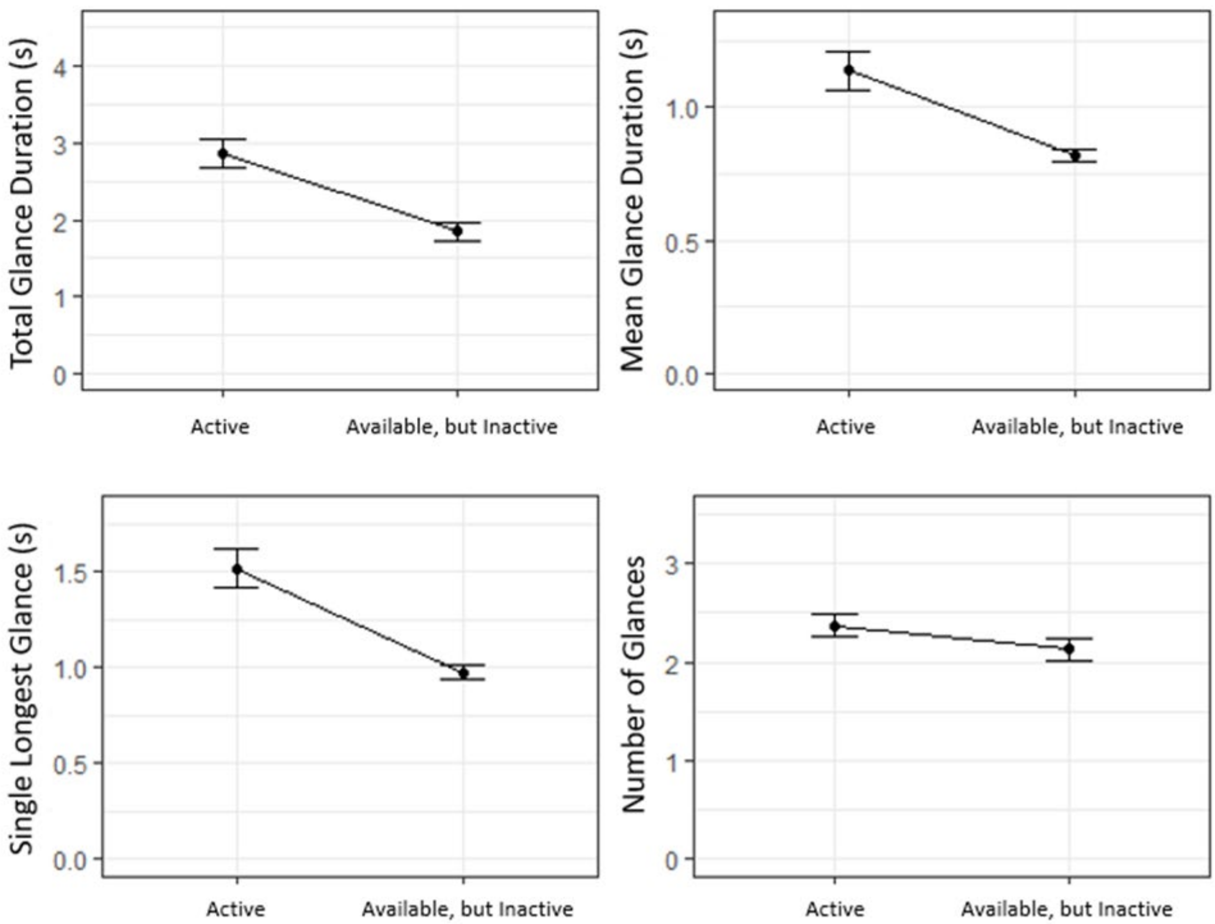
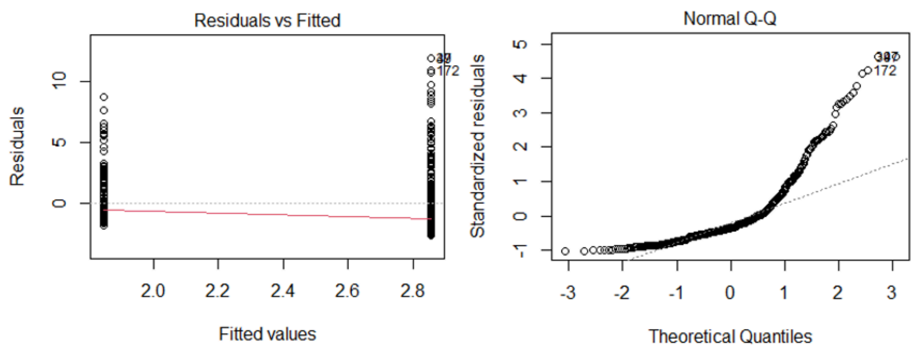
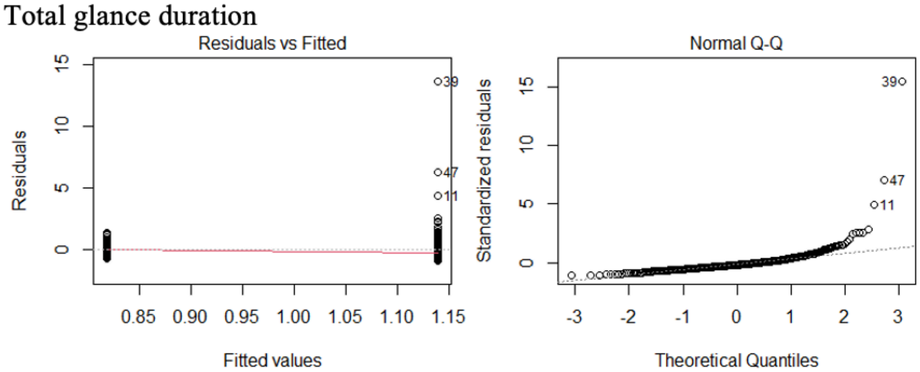


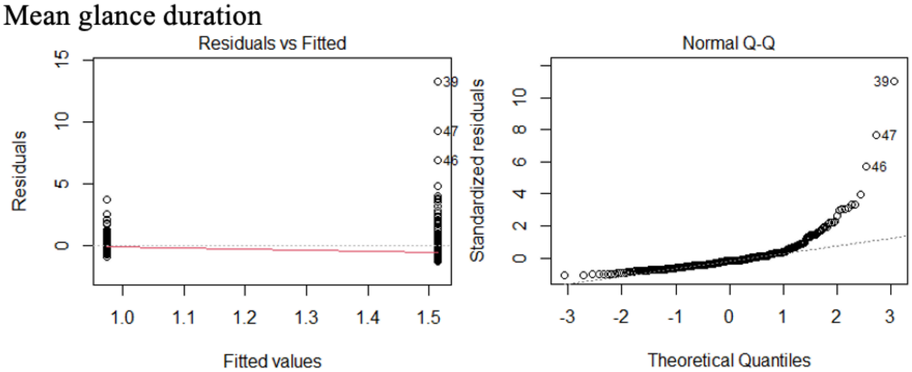
Figure 22. Total eyes-off-road time (top left), mean glance off-road duration (top right), single longest off-road glance (bottom left), and number of off-road glances (bottom right), for experienced L2 drivers (VCC50 Elite NDS)



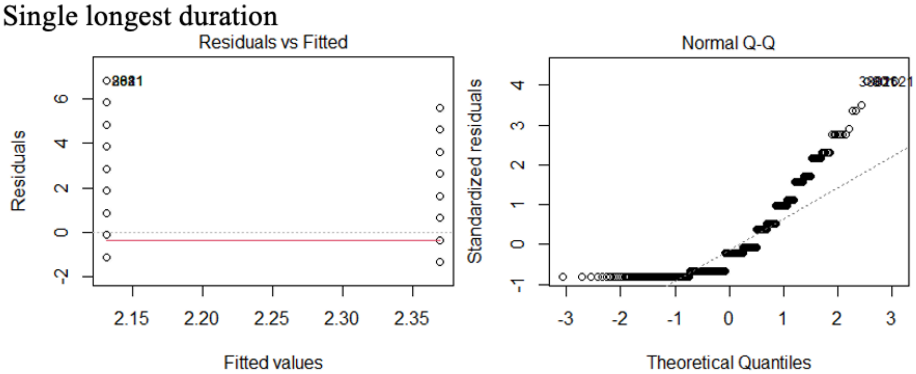
Total glance duration



Mean glance duration



Single longest duration



Number of glances

Figure 23. Assumption check for total eyes-off-road time (top left), mean glance off-road duration (top right), single longest off-road glance (bottom left), and number of off-road glances (bottom right), for experienced L2 drivers (VCC50 Elite NDS)

Secondary Task Engagement

Are drivers more likely to engage in secondary tasks while using driving automation systems, and how does this vary by their level of driving experience with the system?

Inexperienced L2 drivers (L2 NDS) Analysis

To answer this research question, drivers' secondary task engagement was assessed using the matched sample of cases (L2 systems active) and matched sample controls (L2 systems available but inactive). A generalized linear model was conducted to assess significant differences of frequency of secondary task engagement. There were no significant main effects for secondary task prevalence between the two types of L2 system status (Figure 24), nor were there any significant differences across exposure phases (Figure 25). The model output is shown in Table 10. For both activation levels (L2 systems available and available but inactive), there were no secondary tasks observed in 37 percent of cases (white), while the remaining samples contained at least one secondary task (blue and red bars).

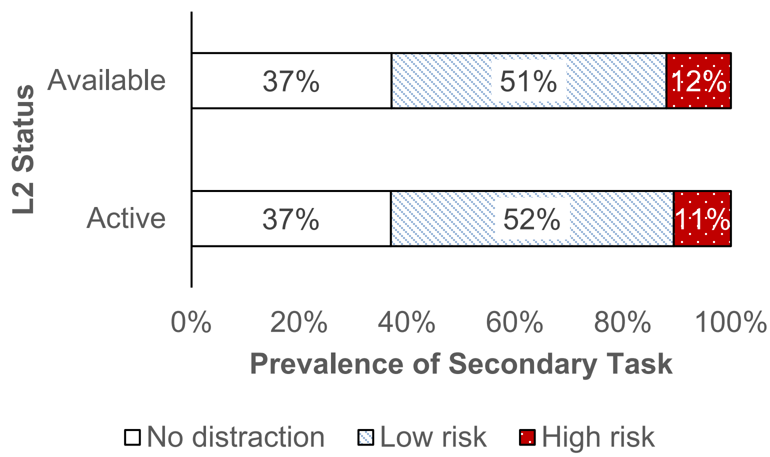


Figure 24. Secondary task by L2 status for inexperienced L2 drivers (L2 NDS)

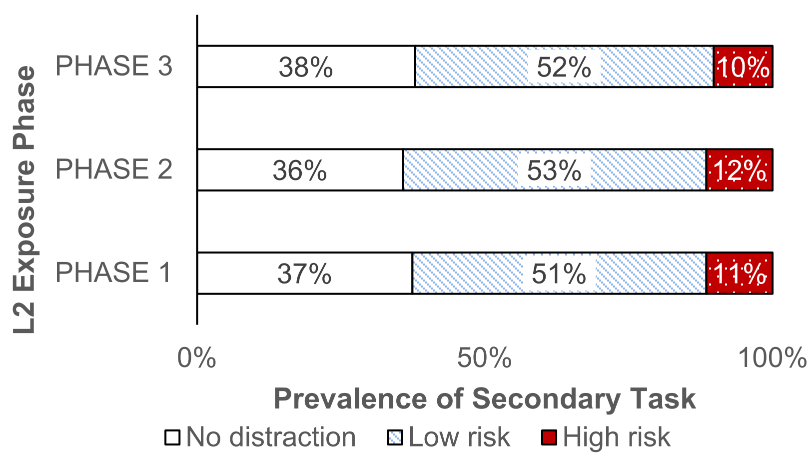


Figure 25. Secondary task risk level by L2 exposure phase for inexperienced L2 drivers (L2 NDS)

Analysis of the interaction between L2 system status and L2 exposure phase showed a statistically significant interaction (z value = -2.806, p = .05). As shown in Figure 26, high-risk secondary task prevalence increased over time when L2 systems were active. High-risk secondary task prevalence decreased when L2 was available but not active.

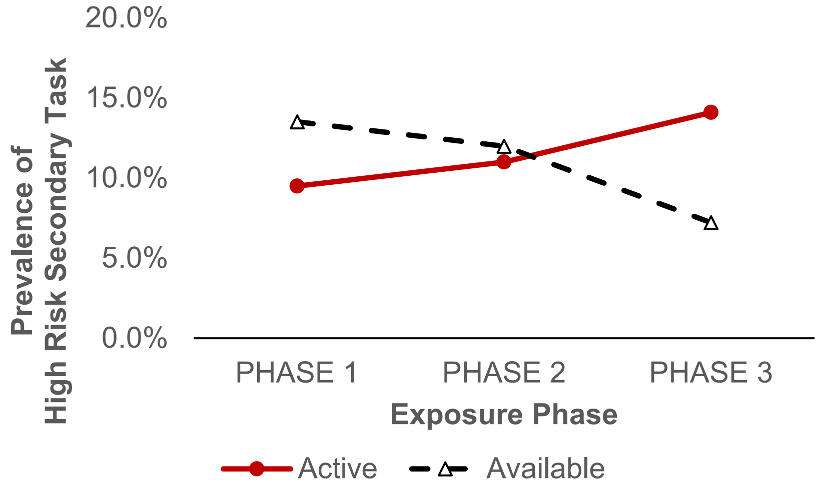


Figure 26. The interaction of L2 status by exposure phase for prevalence of engagement in high-risk secondary tasks

Table 11 shows the results of the logistic regression analysis for engagement in high-risk secondary tasks. Whether a driver engaged in high-risk secondary tasks or not is a binary variable. Logistic regression is based on a logistic function that can evaluate the influence of impacting factors on the probability of engaging in high-risk secondary tasks. Key independent variables include phase, L2 status, road type, lighting, and an interaction term between phase and L2 status. A random effect allocated across participants was also considered in the model. Overall, drivers were around two times more likely to undertake a high-risk secondary task after 8+ hours of exposure compared to 0–3 hours of exposure to L2 systems. Furthermore, drivers were more likely to undertake high-risk secondary tasks on non-divided roads versus divided roads.

Table 10. Logistic Regression for High-Risk Secondary Task Engagement for Inexperienced L2 Drivers (L2 NDS)

Variables	Estimation	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	*p*
Intercept	0.084	0.059	0.121	< .001
Available versus Active	1.379	0.935	2.031	0.105
Phase 1 versus Phase 2	1.223	0.762	1.963	0.405
Phase 1 versus Phase 3	2.047*	1.138	3.681*	0.017
Darkness (lighted) versus Daylight	0.915	0.586	1.427	0.694
Darkness (not lighted) versus Daylight	0.612	0.365	1.024	0.061

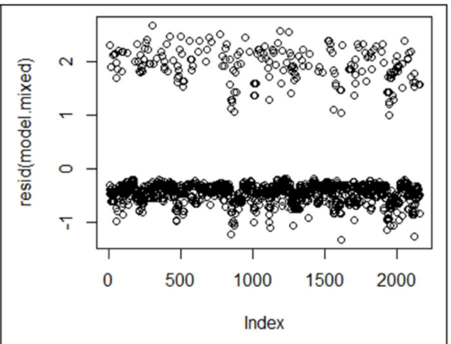
Variables	Estimation	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	*p*
Dawn/Dusk versus Daylight	0.541	0.223	1.315	0.175
Not divided (2-way) versus Divided	2.783*	1.808*	4.285*	< .001
One-way traffic versus Divided	0.825	0.433	1.573	0.559
Interaction: Available*PHASE 2	0.696	0.366	1.323	0.269
Interaction: Available*PHASE 3	0.294*	0.127	0.681	.04

*Indicates statistically significant result.

The multi-collinearity and model fit is shown in Figure 27, below, illustrating that all covariates have a variance inflation factor (VIF) of less than 4, which indicates no multi-collinearity issues. The residual plot implies that the model fit is good, with an AIC of 1,456.2.

Covariate	GVIF	Df	GVIF^(1/(2*Df))
ADAS	1.90	1	1.38
PHASE	3.57	2	1.38
LIGHTING	1.03	3	1.01
TRAFFICFLOW	1.13	2	1.03
ADAS:PHASE	4.86	2	1.48

a) Multi-collinearity check



b) Residual check

*GVIF: generalized variance inflation factor; Df: degrees of freedom.

Figure 27. Assumption check for high-risk secondary task mixed-effect logistic regression of inexperienced L2 drivers (L2 NDS)

Experienced L2 Drivers (VCC50 Elite NDS) Analysis

The results for the experienced L2 drivers from the VCC50 Elite NDS show a slightly different pattern. Analysis of experienced L2 drivers showed a significant main effect of activation level (Table 11). As shown in Figure 28, drivers were observed to undertake high-risk secondary tasks 17 percent of the time when L2 was active compared to only 13 percent of the time when L2 was available but not active. Table 11 shows the results of two logistic regression models. The first logistic regression analysis compares the presence of high-risk secondary task engagement to anything else the driver may be doing (e.g., low risk secondary task engagement or no secondary task engagement). The second logistic regression analysis compares any secondary task engagement (high risk secondary task engagement or low risk secondary task engagement) to driving while alert (e.g., no secondary task engagement). Experienced L2 drivers were more likely to undertake high-risk secondary tasks during the day compared to at night. Additionally, the logistic regression model also suggested that experienced L2 drivers were also less likely to engage in high-risk secondary tasks when L2 systems were available but inactive than when they were active. A logistic regression was also conducted for engagement in any type of secondary task; the results are available in Appendix C.

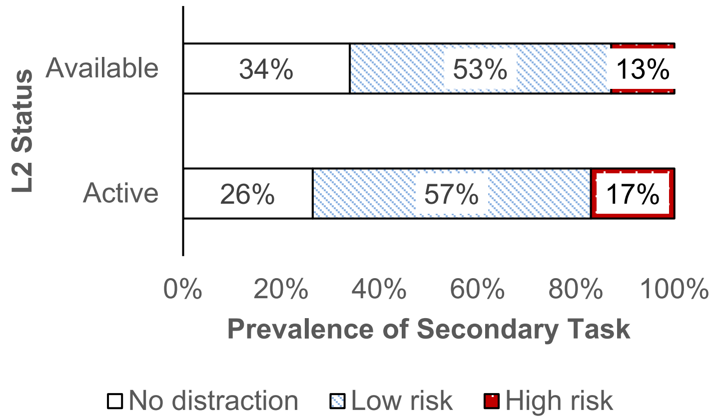


Figure 28. Secondary task engagement for experienced L2 drivers (VCC50 Elite NDS)

Table 11. Logistic Regression for High-Risk and Secondary Task Engagement for Experienced L2 Drivers (VCC50 Elite NDS)

VCC data	**High-risk secondary task= 1; low risk secondary task or no secondary task = 0**				**High-risk and low-risk secondary task = 1; no secondary task = 0**			
Variables	**Estimation**	**95% Confidence Interval Lower Bound**	**95% Confidence Interval Upper Bound**	***p***	**Estimation**	**95% Confidence Interval Lower Bound**	**95% Confidence Interval Upper Bound**	***p***
(Intercept)	0.135	.067	0.272	<.001	3.390	2.452	4.686	<.001
Available versus Active*	**0.636**	**.412**	**0.981**	.041	**0.631**	**0.460**	**0.868**	.05
Darkness (lighted) versus Daylight	0.838	.467	1.504	.554	0.671	0.443	1.016	.059
Darkness (not lighted) versus Daylight*	**0.411**	**.194**	**0.875**	.021	**0.639**	**0.414**	**0.987**	.04
Dawn/Dusk versus Daylight	1.178	.455	3.050	.736	0.944	0.399	2.234	.896
Not divided (2-way) versus Divided	1.605	.802	3.214	.182	1.306	0.760	2.245	.334
One-way traffic versus Divided	1.055	.482	2.307	.894	1.344	0.732	2.466	.340

*Indicates result is statistically significant.

Objective 2: Determine what factors influence how drivers rely on, and adapt to, L2 systems.

What is the relationship of driving time when L2 systems are active versus when L2 systems are available but inactive for both inexperienced (L2 NDS) and experienced (VCC50 Elite NDS) L2 drivers?

Figure 29 shows a plot of the inexperienced L2 drivers (L2 NDS) where total driving time (minutes) is plotted on the x-axis and cumulative L2 system activation time (minutes) is plotted on the y-axis for individual participants. This plot provides a visualization for the relationship between driving time with L2 active versus total driving time. Therefore, any horizontal line segment represents accumulation of total driving time (i.e., without L2 system activation) and any vertical line segment represents accumulation of driving time with the L2 system active for that participant.

The figure is divided into quadrants representing the points prior to and after Phase 3 (480 minutes, or 8 hours of cumulative driving time), and the points prior to and after the mean total driving time (mean = 3,444 minutes, median = 3,260 minutes). Quadrant 3 represents all drivers in the first 8 hours of driving. Quadrant 4 represents the drivers who drove more frequently without L2 systems active in the first 8 hours of L2 system activation. Quadrant 2 shows those drivers who exceeded 8 hours of cumulative L2 system driving and drove most of their driving time with L2 systems active. Quadrant 1 represents those drivers who also drove with L2 systems active for over 8 total hours but accumulated L2 system exposure more gradually over the course of the study than the group in Quadrant 2. Generally, drivers gradually accumulate their exposure to L2 automated systems over driving time. There does not appear to be a pattern of curved exposure to L2 automated systems, which would suggest either rapid initial use that tapers off or initial disuse that changes to very frequent use. However, Quadrant 4 does have some examples of drivers who initially used L2 systems and then stopped using them as frequently.

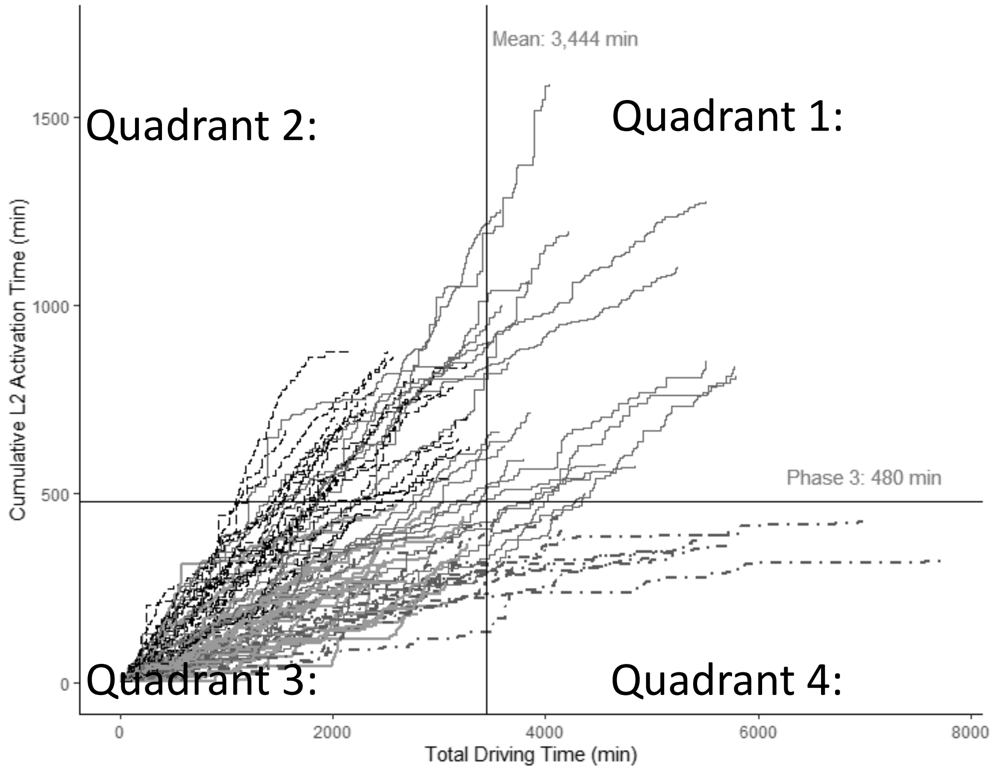


Figure 29. Plot of L2 NDS individual drivers total driving time (x-axis) by cumulative L2 automated system activation time (y-axis).

Quadrants 1–4 based on 8 hours of cumulative drive time and mean total driving time. (Solid gray lines terminate in Quadrant 1, dashed black lines terminate in quadrant 2, solid black lines terminate in quadrant 3, and dashed black lines terminate in quadrant 4.)

Figure 30 shows the plot for the experienced L2 drivers (VCC50 Elite NDS). For this plot, only the mean driving time (minutes) are shown in the figure, creating two segments. The left segment represents those drivers who drove relatively less frequently, and the right segment represents those drivers who drove relatively more frequently. While overall driving time is much greater for these experienced drivers than for the inexperienced L2 drivers from the L2 NDS (12 months of data collection for VC50 NDS drivers), the same linear pattern is presented where L2 activation appears to gradually increase as driving time increases. There do not appear to be any curved lines indicating frequent use followed by very little use or vice versa.

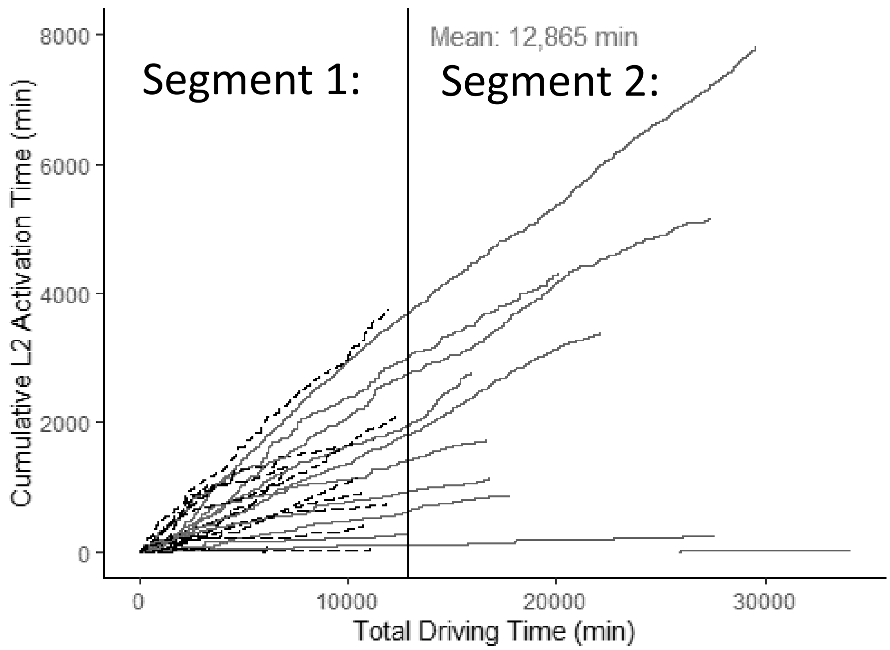


Figure 30. Plot of total driving time (x-axis) by cumulative L2 automated system activation time (y-axis) for experienced L2 drivers (VCC50 Elite NDS).

Solid black lines terminate in segment 2 and dashed black lines terminate in segment 1.

Time of Day

During what TOD are drivers more likely to activate their L2 systems for inexperienced L2 drivers (L2 NDS) and experienced L2 drivers (VCC50 Elite NDS)?

This analysis used the exposure metrics to assess the percentage of time driving with L2 active by TOD. TOD was parsed into blocks of time that represent commuting times (i.e., 5 a.m. to 7:59 a.m. and 4 p.m. to 6:59 p.m.), middle of the day (8 a.m. to 11:59 p.m. and 12 p.m. to 3:59 p.m.), evening (7 p.m. to 9:59 p.m.) and very late night or early morning (10 p.m. to 12:59 a.m. and 1 a.m. to 4:59 a.m.). For these analyses, subjects were used as a random effects variable to eliminate any subject-level effects. Tests for normality and homogeneity of variance showed that the assumption was not violated, as shown in Figure 31 and Figure 32 below.

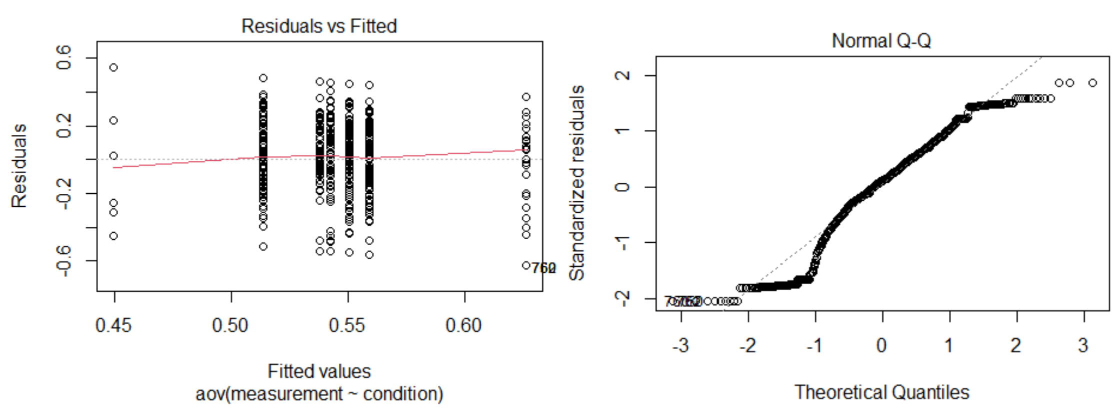


Figure 31. Assumption check for ANOVA test for percentage of driving time under activation by TOD for inexperienced L2 drivers (L2 NDS)

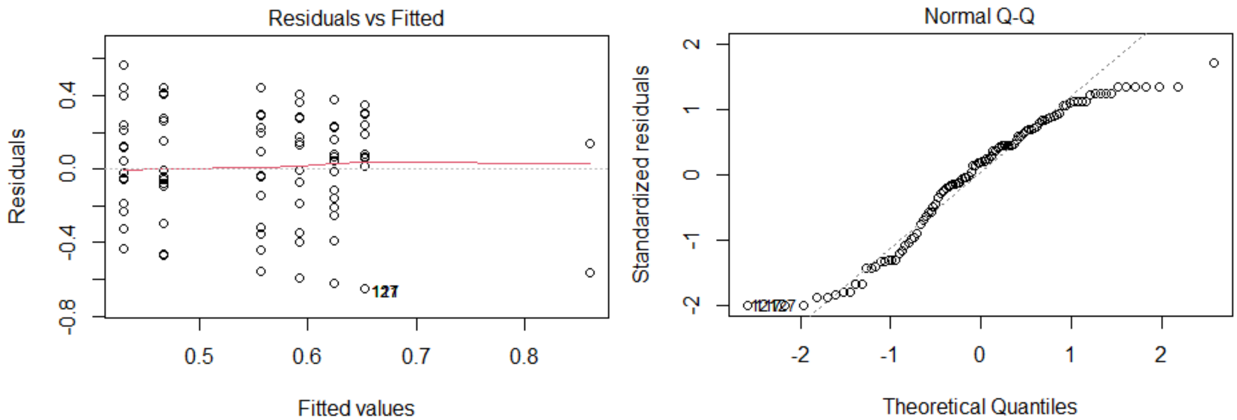


Figure 32. Assumption check for ANOVA test for percentage of driving time under activation by TOD for experienced L2 drivers (VCC50 Elite NDS)

An ANOVA was conducted to assess whether any differences existed in the percentage of time driving with L2 systems by TOD and L2 activation group. Figure 33 and Figure 34 show the percentage of time of L2 activation by TOD for the experienced and inexperienced L2 drivers, respectively. The results did not show a main effect of either L2 activation group or TOD, and TOD did not impact the decision to use L2 systems ($F(6,562) = 0.98$, $p = .439$ for TOD, $F(2,562) = 0.485$, $p = .626$ for L2 status for inexperienced L2 drivers [L2 NDS]). The analysis for the experienced L2 drivers (VCC50 Elite) found a similar nonsignificant result for percentage of driving time with L2 activation by TOD, $F(6, 95) = 1.526$, $p = .178$).

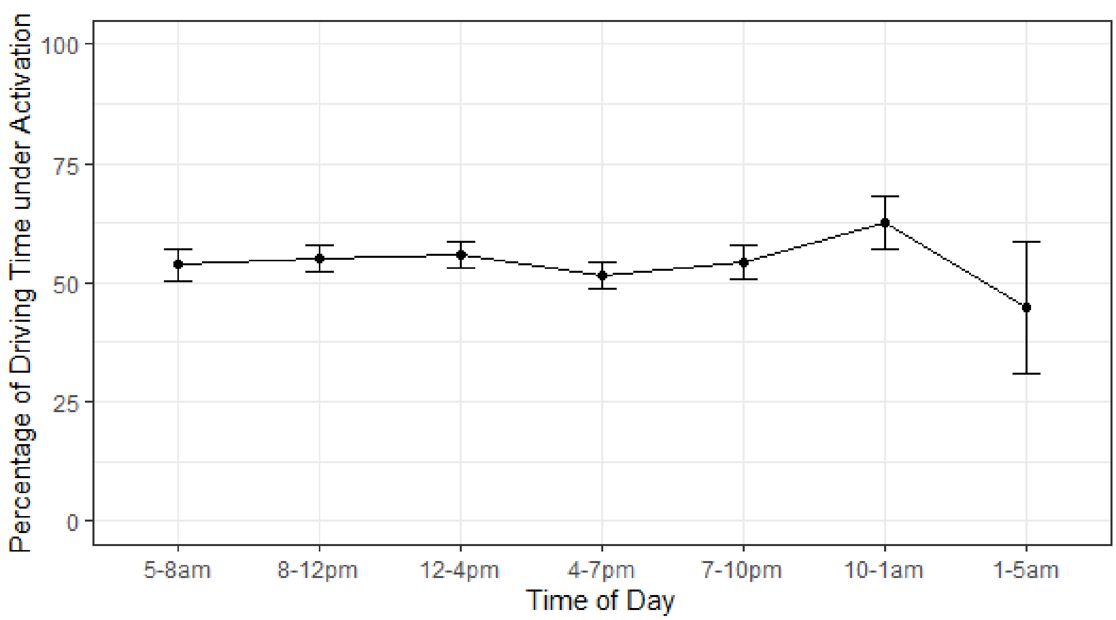


Figure 33. Percentage of driving time for inexperienced drivers with L2 systems active by TOD with standard error bars for inexperienced L2 drivers (L2 NDS)

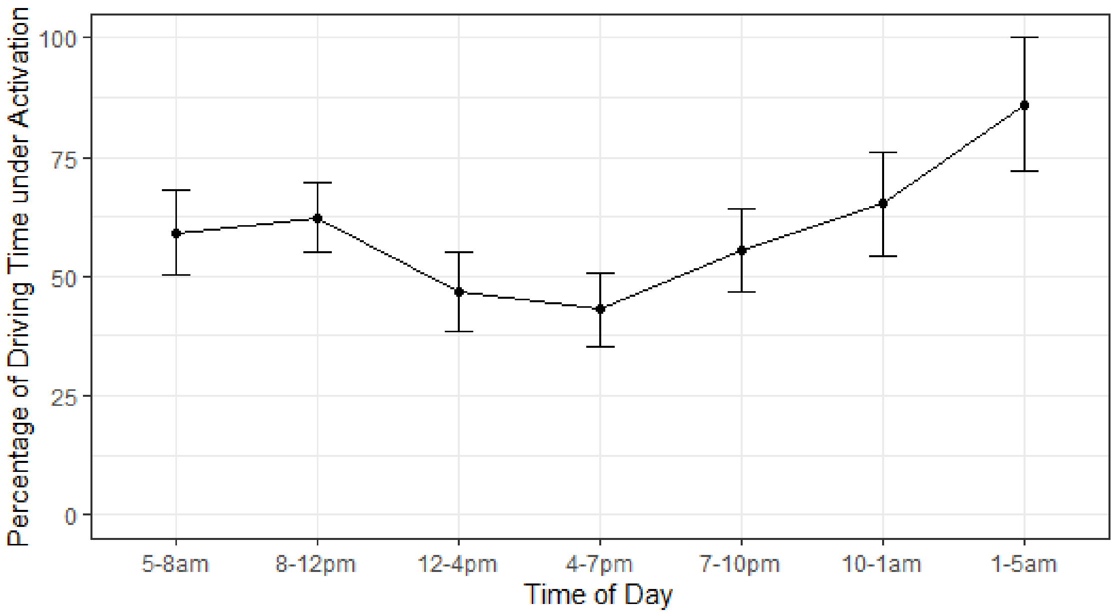


Figure 34. Percentage of driving time with L2 systems activated by TOD for experienced L2 drivers (VCC50 Elite NDS)

During what TOD are drivers more likely to activate their L2 systems by phase?

An ANOVA was also conducted to assess whether the percentage of time driving with L2 systems active by TOD changes over time. The model used TOD, exposure phase, and L2 activation group as independent factors in the model. There were not significant differences between the two L2 activation groups (i.e., those who had longer versus shorter total duration of activation) ($F(1, 561) = 1.89$, $p = .170$). Figure 35 shows the inexperienced L2 drivers' (L2 NDS) percentage of driving using L2 systems by TOD and phase. Note there is only one participant during the 1–5 a.m. group in Phase 1, and they did not use L2 activation. There was no main effect of either TOD or phase ($F(6,561) = 0.99$, $p = .430$ for TOD; and $F(2, 561) = 0.45$, $p = .639$ for phase).

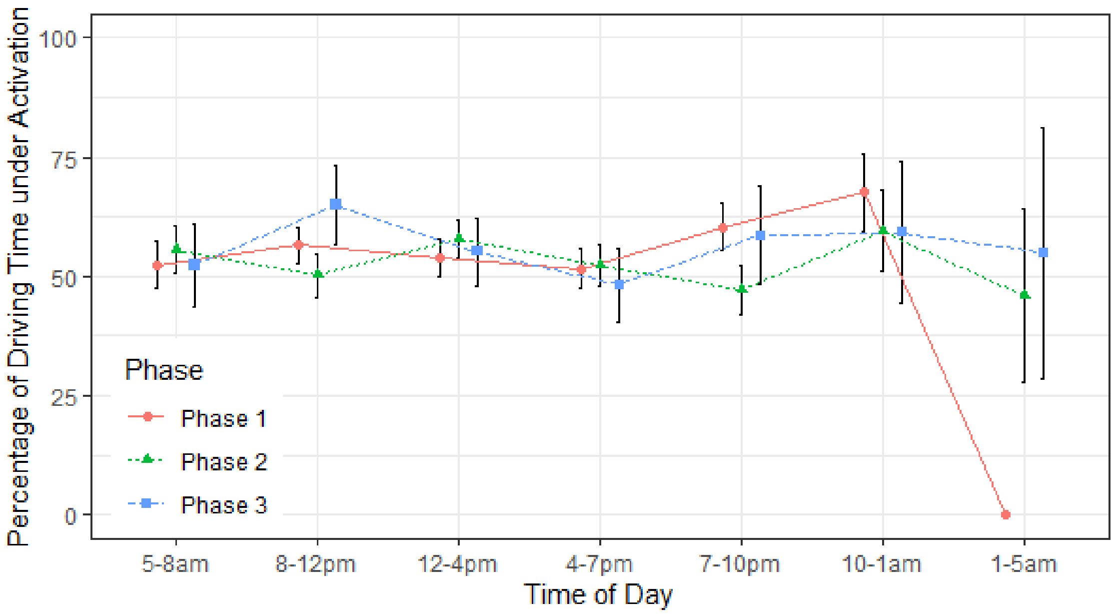


Figure 35. Percentage of driving time with L2 systems activated by TOD and exposure phase for inexperienced L2 drivers (L2 NDS)

The assumption checks for the ANOVA are shown in Figure 36 below. Homogeneity of variance and normality were not violated.

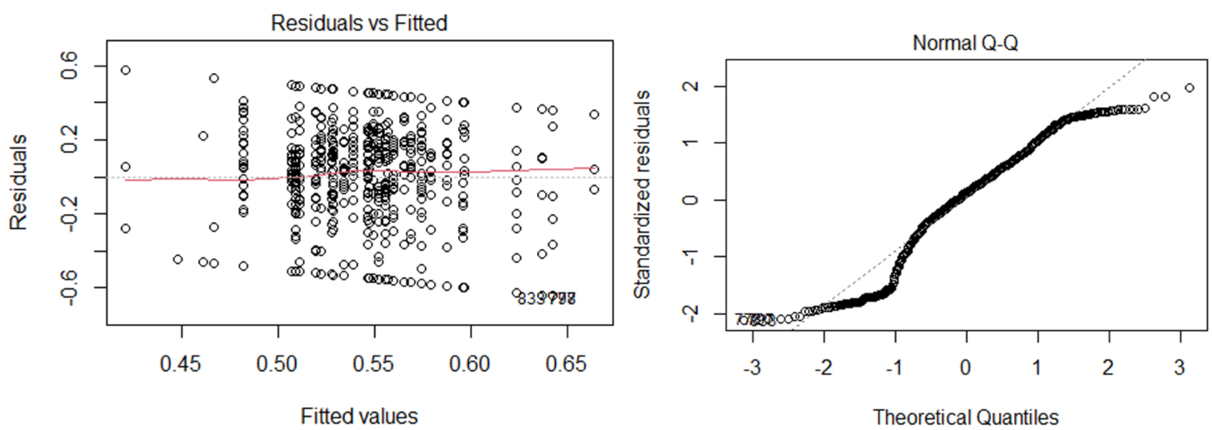


Figure 36. Assumption check for percentage of driving time by TOD

Day of Week

During what day of the week (weekdays versus weekends) are experienced (VCC 50 Elite NDS) and inexperienced L2 (L2 NDS) drivers more likely to activate their L2 systems?

Exposure data was also used to determine whether day of week (i.e., weekday versus weekend) affected the percentage of L2 activation time. For the inexperienced L2 drivers (L2 NDS), L2 activation group (longer or shorter total L2 use) was an independent variable in the model and was statistically significant ($F(1, 117) = 6.86$, $p = .010$). Figure 37 shows the inexperienced drivers' percentage of driving time by day of week. There was no significant difference in percentage of driving time with activation of L2 systems between weekdays versus weekends ($F(1, 117) = 0.14$, $p = .706$).

The ANOVA assumption check is shown in Figure 38.

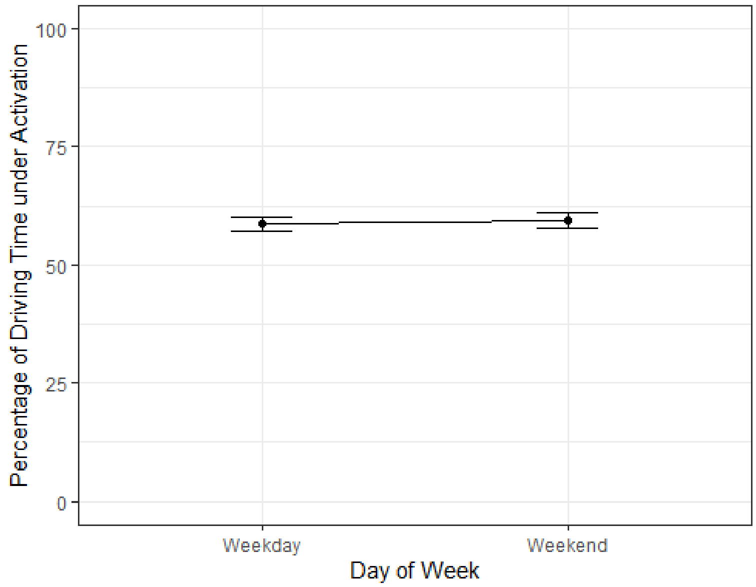


Figure 37. Percentage of driving time with L2 systems activated by day of week for inexperienced L2 drivers (L2 NDS)

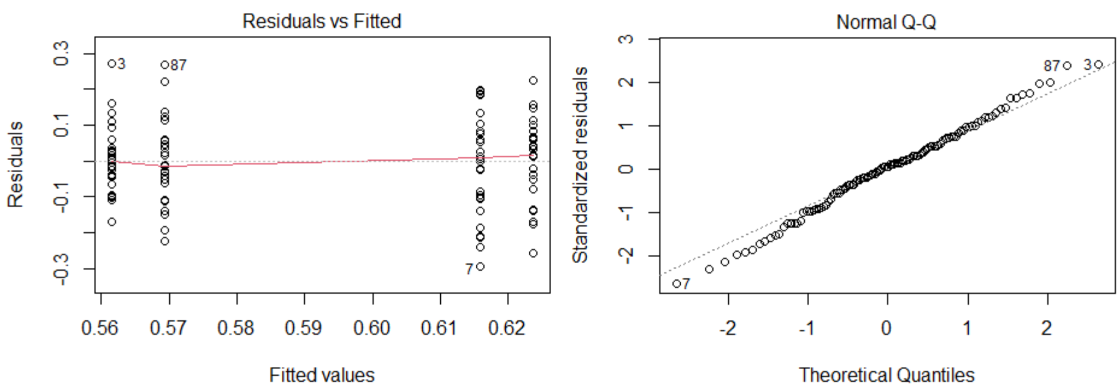


Figure 38. Assumption check of ANOVA for inexperienced L2 drivers (L2 NDS)

The analysis for the experienced drivers (Figure 39) also indicated no significant difference in percentage of activation of L2 systems by day of week ($F(1,38) = 0.09$, $p = .767$).

The assumption check for the ANOVA is shown in Figure 40.

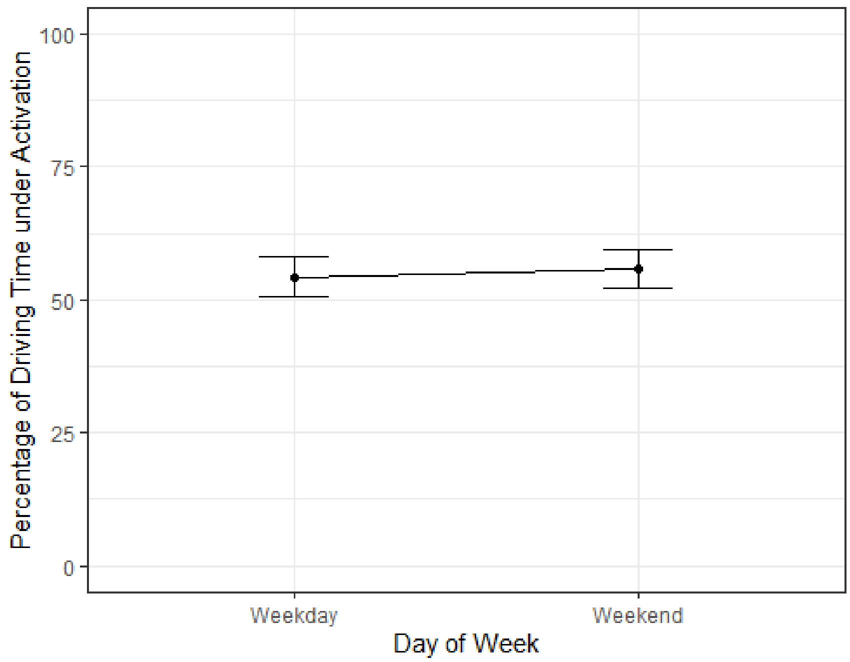


Figure 39. Percentage of driving time with L2 systems activated by day of week for experienced L2 drivers (VCC50 Elite NDS)

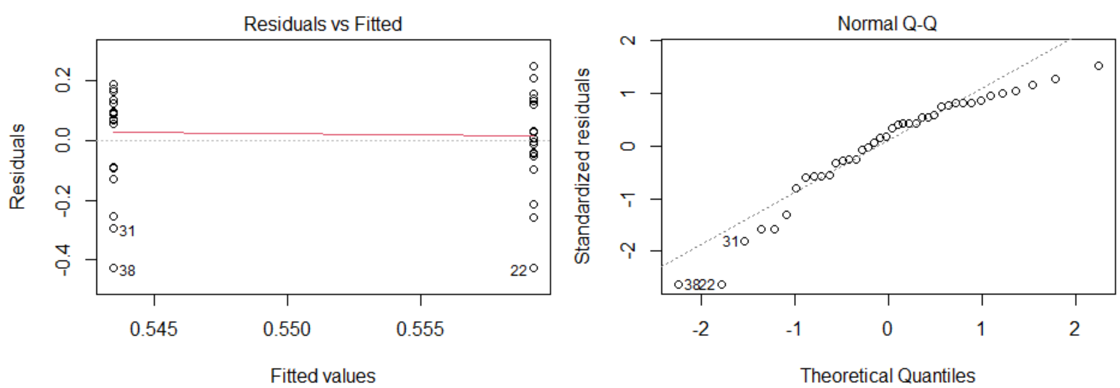


Figure 40. Assumption check for ANOVA experienced L2 drivers (VCC50 Elite NDS)

Road Type

On what road types are drivers more likely to activate their L2 systems for experienced (VCC50 Elite NDS) and inexperienced (L2 NDS) L2 drivers? On what road types are drivers more likely to activate their L2 systems by phase?

The L2 activation metrics were also used to assess whether drivers were more likely to activate L2 systems on Functional Class 1 (controlled access roadways) versus Functional Class 2 through Functional Class 6 (non-controlled roadways ranging from highways to local roads) roadways. An ANOVA indicated no significant differences by phase, or road type ($F(2,2) = .0$, $p = 1.00$ for phase; $F(1,2) = 1.02$, $p = .419$ for road type). Figure 42 demonstrates that drivers were just as likely to activate L2 systems on controlled-access roadways as they were to activate L2 systems on uncontrolled-access roadways, and this effect did not change over time (phase).

The same analysis was conducted for the experienced L2 drivers (VCC50 Elite NDS). Similar results were found from the chi-square test, with only slightly more L2 system activations occurring on controlled-access roadways versus uncontrolled-access roadways ($\chi^2(1, N =$ 7,481)= 48.26, $p < .001$) (Figure 42).

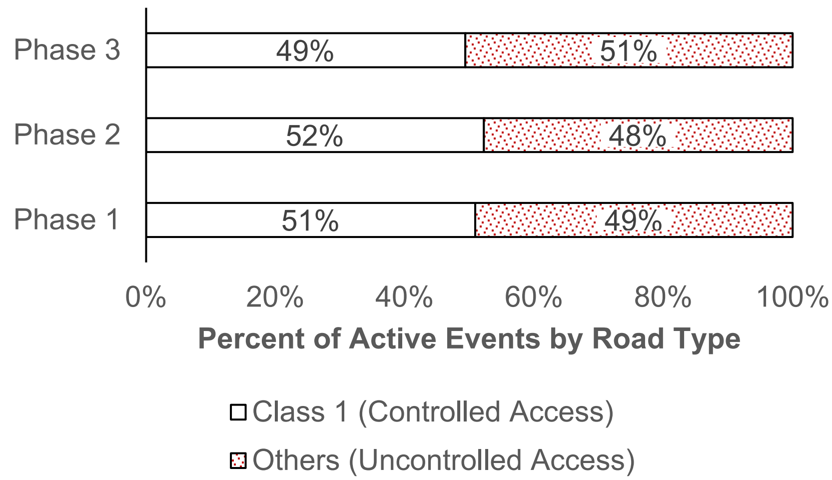


Figure 41. Percentage of active events for inexperienced L2 drivers (L2 NDS) by road type through 6 roadways across each L2 exposure phase

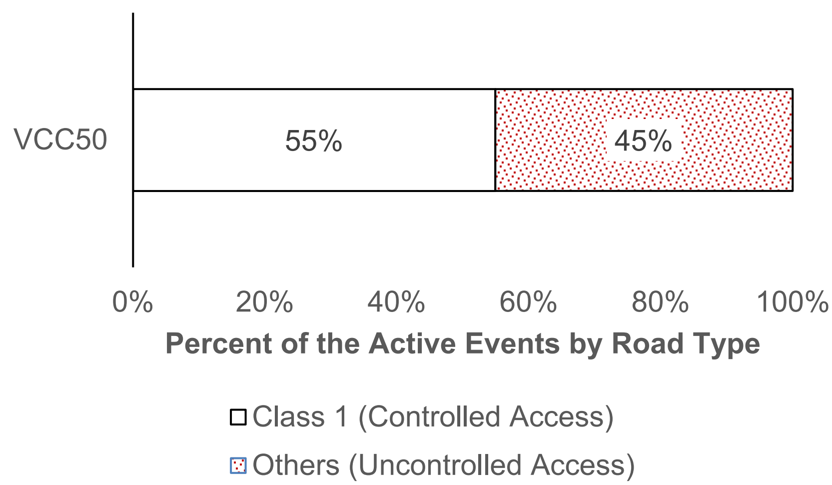


Figure 42. Percentage of active events by road type through 6 roadways across each L2 for experienced drivers (VCC50 Elite NDS)

Objective 3: Determine whether there are relevant outcomes of adaptation and reliance upon L2 systems.

Request to Intervene Analysis

There was a total of 1,766 RTIs for the inexperienced L2 drivers L2 NDS). Sixty-three of the 82 participants (77%) received at least one RTI, and among drivers who experienced RTIs, 40 had less than 10 RTIs. Figure 43 displays a histogram of the RTIs for the inexperienced L2 drivers (L2 NDS).

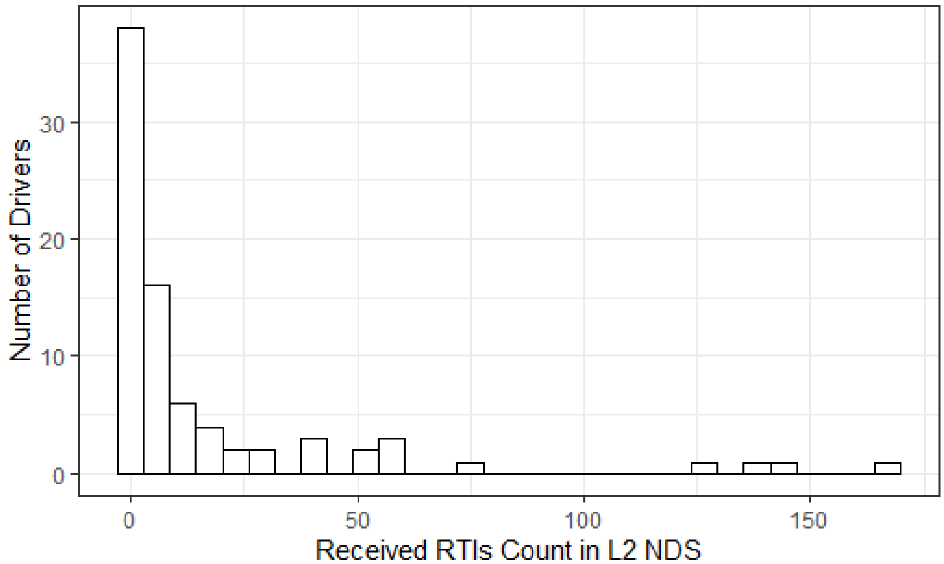


Figure 43. A histogram for frequency of RTIs across drivers

What is the rate of RTIs per unit time of L2 driving by exposure group?

The frequency of RTIs was divided by the total duration of L2 system activation to obtain the rate of RTIs per hour of L2 activation. An ANOVA was conducted looking at exposure phase and L2 activation group (longer or shorter total activation time); however, no significant results were found for phase or for L2 activation group ($F(2,199) = 0.93$, $p = .397$ for phase; and $F(1, 199) = 1.21$, $p = 0.273$ for driver group). Figure 44 shows the rate of RTIs by phase, indicating a decreasing, albeit not significant, trend.

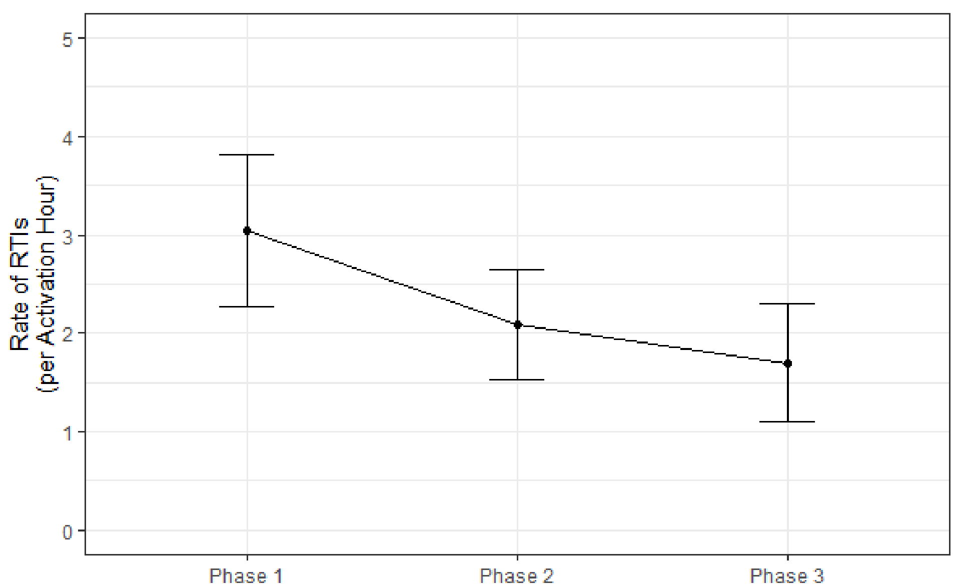


Figure 44. Rate of RTIs per activation hour for each L2 exposure phase for inexperienced L2 drivers (L2 NDS)

The assumption check is shown in Figure 45 below. There are few outliers, but overall, the assumption is not violated.

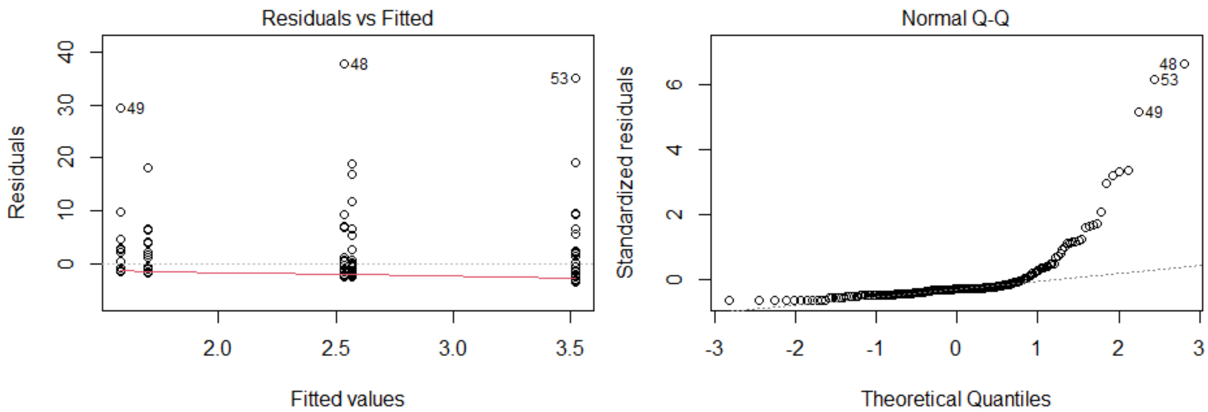


Figure 45. Assumption check for ANOVA for inexperienced L2 drivers (L2 NDS)

Are drivers more likely to receive RTIs during specific time(s) of day (TOD)? Does this vary by phase?

The rate of RTIs by hour of driving and phase with L2 systems active was also used to assess whether drivers tended to receive RTIs more frequently during a certain TOD or by exposure phase. An ANOVA was conducted, which indicated (see Figure 46) that the main effect of TOD was not significantly different (F(6, 889) = 0.95, p = .455) but that exposure phase was significant, F(2, 889) = 3.022, p = .049). A post hoc Tukey test was conducted that indicated Phase 1 was significantly different from Phase 3 (p = .05). No differences existed between Phase 1 and Phase 2 (p = .11) and Phase 2 and Phase 3 (p = .87). The assumption check for the ANOVA is presented in Figure 47.

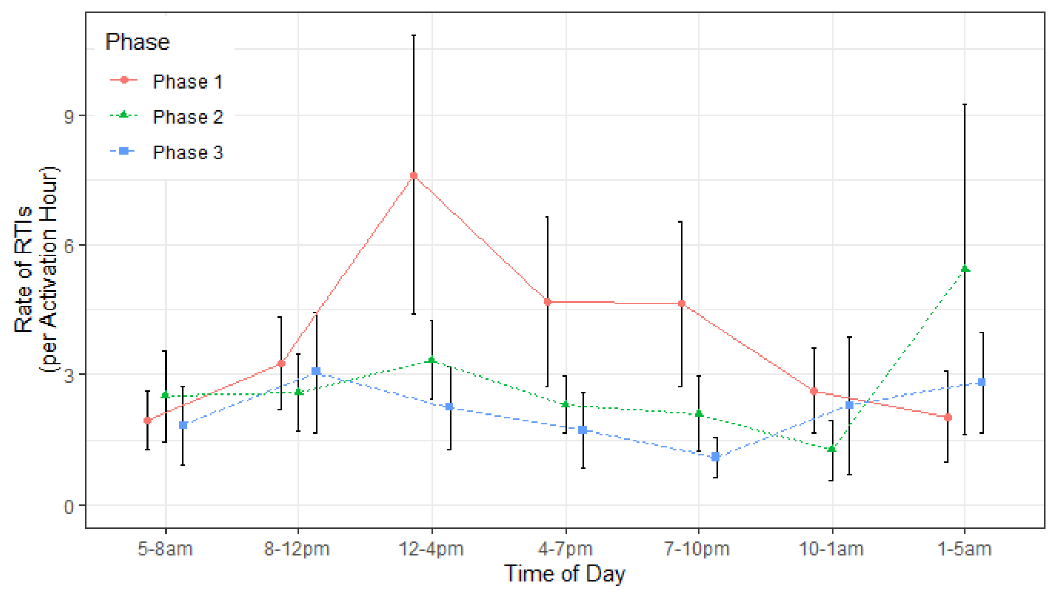


Figure 46. The rate of RTI activation by TOD and by exposure phase for inexperienced L2 drivers (L2 NDS)

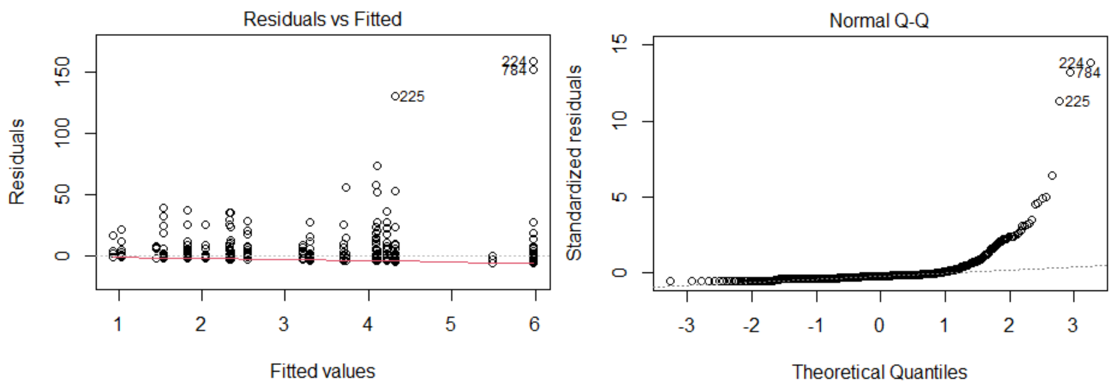


Figure 47. Assumption check ANOVA for inexperienced L2 drivers (L2 NDS)

Are drivers more likely to receive RTIs during a weekday versus a weekend? Does this vary by phase?

An ANOVA was conducted to assess whether drivers received RTIs at different rates by day of week (i.e., weekday versus weekend) and exposure phase. There were no statistically significant results found for this analysis ($F(1,2) = 0.02$, $p = .904$ for week) but there were significant differences among phases ($F(2,2) = 37.38$, $p = .026$ for phase).

Are drivers more likely to receive RTIs under specific traffic conditions (road type)? Does this vary by phase?

A chi-square test was conducted on the number of RTIs that occurred by road type and exposure phase. This was a slightly different analysis than those that were conducted for the previous research questions focused on RTIs. The previous questions were evaluated by using a rate of RTI by hour traveled with L2 active. Instead, for this analysis, the type of road that the driver was traveling at the time of each RTI occurrence was identified and the frequency of RTI by road type was calculated. See Figure 48 for these results. The chi-square analysis indicated significant differences in road type and exposure phase, ($\chi^2(2, N = 1{,}495) = 37.05$, $p < .001$).

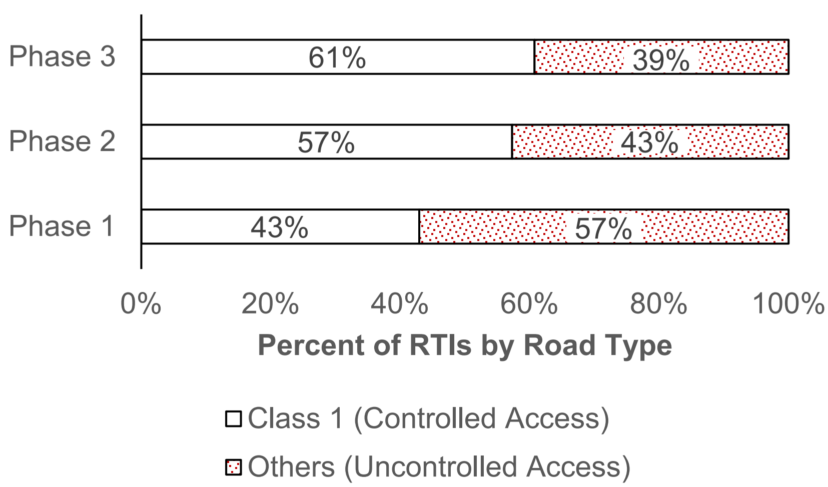


Figure 48. The frequency of RTIs by exposure phase and road type

Objective 4: Evaluate the lessons learned from using L2 systems in vehicles.

This section will focus on the statistical results from the previous three objectives to evaluate the best practices and lessons learned from drivers using L2 systems in vehicles. The introduction to this report discussed using risk allostasis theory to evaluate and potentially predict behavioral adaptation for drivers using driver assistance technologies (Kinnear & Helman, 2010). Risk allostasis theory incorporates the driver's feelings of risk, task difficulty, and workload. As task difficulty and workload decrease with L2 systems active, the observable behavioral result may be increased eyes-off-road time or more frequent higher risk secondary tasks. It has been established in the literature that behaviors such as speeding, higher risk secondary task engagement (i.e., tasks that require both eyes-off-road and hands off steering wheel), and glances off road can represent higher risk. The driving task becomes easier or less demanding when the L2 systems take over the tasks of lateral and longitudinal control (i.e., workload or task difficulty decreases). The driver's decrease in workload may result in engagement of other activities that brings workload back to a comfortable level. The rest of this section will discuss the results where significant differences in driver behaviors were observed over time to assess whether these differences may be due to driver adaptation to L2 systems. The following discussion is focused on the inexperienced L2 drivers (L2 NDS) only, as this was the only group that was evaluated over time.

Accumulated Use of L2 Systems

Drivers in the longer L2 activation group quickly accumulated L2 driving time (mean of 7.3 days, Figure 44), whereas the drivers in the shorter L2 activation group accumulated L2 driving time much less quickly (mean of 13.2 days). This result makes intuitive sense. As the group who uses L2 systems more accumulates driving time with L2 activation, the result will be longer total durations of L2 activation exposure. Additionally, drivers in this group experience a more intense exposure period with longer sessions of L2 system use that may result in improved learning. If a driver who is inexperienced with L2 systems uses these systems frequently over the course of several days, this driver will also receive frequent feedback regarding using the controls to initiate L2 systems, observing how ACC responds to lead vehicles, how the lateral control system responds to lane markings, and even the presentation of RTIs. This period of intense system use, and feedback regarding system use over a short period of time may provide some benefits in that users may form a more accurate framework in which to organize their future experiences with L2 systems.

Driver Behaviors

Speed Selection

The results of the overall speeding analyses suggested that drivers increase the speed at which they initiate L2 systems over time. Recall that the driver's speed selection at onset of L2 feature activation was evaluated during the first 3 hours of L2 system use (Phase 1), between 3 and 8 hours of L2 system use (Phase 2), and over 8 hours of L2 system use (Phase 3). Results suggested that drivers' speed selection increased to significantly faster speeds between Phases 1 and 2 but not between Phases 2 and 3. This result suggests that, during the transition between Phase 1 and 2, drivers are becoming more comfortable with L2 systems, and their perceived levels of workload are decreasing; thus, they are more comfortable setting L2 systems at higher speeds. This result is also reminiscent of the learning curve shown in Newell and Rosenbloom (1980), as the significant behavior change occurred between the two early phases and then slowed or stopped between Phases 2 and 3. The inexperienced drivers were setting their speeds 10 mph or more above the speed limit in approximately 34 percent of the activations. The experienced drivers were setting their L2 systems at 10 mph or more above the speed limit even more frequently, at 48 percent of the total L2 activations. The evidence of driver adaptation shown by drivers' selecting increasing speeds over time and the greater frequency of traveling 10 mph or greater above the speed limit in experienced users have important implications. Possible research strategies to mitigate these concerns could include investigating geofencing or geospatial roadway data to set thresholds to ensure that drivers are not setting ACC or L2 systems too high relative to the speed limit.

Additionally, drivers who had longer total L2 activation time did not increase their speeding by phase, whereas the drivers with shorter total L2 activation time were found to increase their speeding over time. This result may suggest that it took the shorter L2 activation group slightly longer to reach their risk threshold with speeding, whereas the longer L2 activation group had already reached it in the first phase. This may indicate that those drivers with more intense early exposure also learned more quickly and adapted in a shorter time frame.

Glance Behavior

The results indicated that drivers looked away from the forward roadway longer as their experience with L2 systems increased. They also engaged in higher risk secondary tasks more frequently over time. However, the eyes-off-road time observed in these analyses is by no means egregious compared to other studies in the literature. Typically, research has shown that eyes-off-road time of 2 seconds or greater will increase crash/near-crash risk (Klauer et al., 2011, 2014). The mean glance duration in this study was 0.8 seconds, which is well below that 2-second threshold. The same result was found for experienced drivers; however, this analysis only looked at 15-second epochs.

Most of the L2 systems in these studies used hands-on-wheel/torque detectors to assess whether the driver was attentive. If the driver's hands were off the wheel for too long, the systems would provide alerts and warnings and potentially disable the L2 system. None of the vehicles in these studies had a driver monitoring system for head or eye-tracking. Driver monitoring systems aim to sense whether the driver is looking forward or not and can provide alerts to drivers to turn their attention back to the forward roadway. Hands-on-wheel detectors and driver monitoring systems are among the strategies for keeping driver attention on the forward roadway and ensuring drivers are still performing their part of the DDT, which is to attentively monitor the environment for obstacles and emerging hazardous situations.

The change in glance durations to the instrument panel are also notable in that glance durations to the instrument panel were significantly longer in Phase 1 and when L2 systems were active (compared to L2 use in Phases 2 and 3), suggesting that drivers were learning these new displays and spending time looking at them to learn how to use them effectively. While the glance durations were significantly longer in Phase 1, the mean glance durations were not egregious when compared to published research. However, it was a noteworthy finding that there were measurable differences in glance duration to the instrument panel in these initial hours of use. Considering a human-centered design and following solid human factors design principles in the development of these displays may help to reduce eyes off road time by reducing the time it takes drivers to learn to use these displays (Campbell et al., 2016).

Safety Outcomes

RTIs

The results of the RTI analysis suggest that rates of RTIs were generally low, with 45 of the 82 participants receiving five or fewer RTIs across the entire study with inexperienced L2 drivers (L2 NDS). The rate of RTI occurrence decreased over exposure phases, suggesting that drivers were learning behaviors to reduce the occurrence of an RTI. However, it is important to note that these RTIs are often included as a vehicle feature to help ensure that drivers are performing their portion of the DDT. Not only do the present results suggest that RTI rates go down over time but that visual-manual tasks can *increase* over time, as can eyes-off-road time. This study suggests that issuing RTIs based solely on hands on the wheel is not an effective method to ensure that the driver is engaged in the driving task and that RTIs can be circumvented by the driver even as they reduce their Object and Event Detection and Response task performance. A driver monitoring system that can assess whether the driver is looking forward and actually performing the Object and Event Detection and Response task would to be valuable as well.

Additionally, the RTIs in this study occurred more frequently on non-controlled access roadways in Phase 1 and RTIs occurred more frequently on controlled access roadways in Phase 3. As these systems are generally designed for controlled access roadways, drivers in Phase 1 may have been using L2 systems features too frequently on non-controlled access roadways and gaining confidence in the systems, thus obtaining more frequent RTIs on controlled access roadways in Phase 3. Additional analyses would need to be conducted to assess driver behaviors surrounding these RTIs, which was out of scope of the current study.

Conclusions

Overall, the results from these analyses indicated that driver behaviors of speed selection, eyes-off-road, and high-risk secondary task engagement all increased with use of L2 systems. As far as safety outcomes are concerned, not enough safety-critical events were identified in these datasets to adequately assess risk of engagement in what are commonly considered high-risk behaviors (e.g., speeding) when L2 systems are active. Although increases in these behaviors were observed, we do not know if they pose the same level of risk with L2 systems active that they pose on legacy vehicles or when L2 systems are inactive. The analyses of RTIs indicated a downward trend of RTIs over time, but the trend was not statistically significant.

The remainder of the Conclusions section will follow the same organization as the results section and provide a discussion of the results presented in the previous section.

Speed Selection With L2 Systems

Generally, drivers tended to select speeds above the speed limit more frequently with L2 systems active compared to similar conditions when L2 systems were available but inactive. This may be indicative of drivers choosing to engage L2 more frequently when the roadways are less congested. While these patterns of speed selection changed over time for inexperienced L2 drivers (L2 NDS), experienced L2 drivers were selecting speeds above the speed limit even more frequently with L2 active between 10 and 20 mph and greater than 20 mph over the speed limit than were the inexperienced L2 drivers (L2 NDS). Thus, what we may be observing in these results is increasing comfort levels with a new vehicle (i.e., increase in speed selection when L2 systems are available but inactive), but also participants reaching their maximum perceived workload levels for speed after 3 to 8 hours of exposure to L2 automated systems.

It is important to understand the strengths and weaknesses of the speed selection metric. The strength is that it is indicative of the speed the drivers chose or were willing to accept when they first initiated L2 systems. It is not a measure of how fast the vehicle actually traveled for the duration of time that L2 systems were active (i.e., drivers may have been following a slower moving vehicle). Additionally, in these studies, the roadway environment was not controlled.

While the matching factors helped to maintain somewhat similar roadway environments for the comparison of L2 active to L2 available but inactive (TOD, day of week, above 40 mph), these matching factors by no means completely controlled for all critical factors. Thus, the result that drivers chose to travel faster than the speed limit more frequently when L2 systems were engaged compared to when these systems were available but inactive was expected. What is most interesting is the increase in speed selection behavior between Phase 1 and Phase 2, and the difference in this increase between inexperienced and experienced drivers. This demonstrates a trend that speed selection increases over time when using L2 systems, which may suggest that perceived workload while using L2 systems decreases with exposure to L2 systems.

Eye-Glance Behavior

As for driver behavior with L2 systems over time, we observed statistically significant increases in mean off-road glance duration, single longest off-road glance duration, and percentage of time eyes-off-road for drivers using L2 systems. We also observed a statistically significant increase in eyes-off-road time when L2 systems were active across exposure phases, in which off-road glances were shorter in Phase 1 than they were in Phase 3. We observed generally longer eyes-off-road time for the experienced L2 drivers in the VCC50 Elite NDS data as well. These results suggest that drivers may have become more comfortable and were willing to look away for longer periods of time. This result is also supported by the analysis of high-risk secondary task engagement, where we also found a significant interaction of secondary-task engagement by phase of L2 exposure when L2 systems were active. This increase may also be indicative of perceived lower workload when driving with L2 systems, and thus, drivers who are willing to engage in other tasks.

While the observation that these behaviors increased over time is important, it is equally important to remember that this analysis is not assessing the actual risk of these behaviors while L2 systems are active. Previous studies have found increased risk of crash occurrence in the presence of these types of visual/manual secondary tasks as well as eyes-off-road time. These previous studies were conducted with legacy vehicles, not vehicles equipped with L2 systems. It is imperative to reiterate that we do not know if these same behaviors increase crash risk while L2 systems are active.

Secondary Task Engagement

The prevalence of any secondary task engagement with L2 active was higher than what has been reported in previous NDSs with legacy vehicles (Dingus et al., 2016). In this analysis, with L2 systems active, drivers were engaging in secondary tasks (high or low risk) in 62 percent of the driving epochs observed. Additionally, the experienced L2 drivers engaged in some type of secondary task even more frequently at 74 percent of the epochs observed. Thus, there is a trend that drivers of L2 systems will engage in some type of secondary task more frequently when L2 systems are active than will drivers of legacy vehicles. The increase in the prevalence of secondary task engagement in this study as well as the increase seen in the eyes-off-road analysis suggests that drivers will adapt by engaging in secondary tasks and increasing eyes-off-road time.

Environmental Factors

The exposure to L2 systems was not observed to differ significantly by TOD or by day of week (weekday/weekend). That the percentage of time that drivers use these systems is unaffected across rush hour (both morning and evening) as well as middle of the day and late at night suggests that TOD is not a primary factor in determining when a driver may choose to engage L2 systems.

Road type (controlled versus uncontrolled access) also played no role in inexperienced L2 drivers (L2 NDS) choosing to engage L2 systems. This may suggest that traffic environment may be more important than whether the road is controlled access or not. L2 systems are generally designed for controlled-access roadways, but it is clear from this analysis that the drivers engaged it just as frequently on non-controlled access roadways. A more in-depth analysis evaluating the context of the traffic environment (i.e., traffic density) may provide more clarity in understanding under which circumstances drivers decide to activate L2 systems.

While there were too few safety-critical events to assess crash or near-crash rates by L2 system activity, RTIs were evaluated for the inexperienced drivers only (RTIs were not available for the experienced driver data set). The analyses indicated that the rate of RTIs decreased with exposure, but the finding was not significant. Additionally, the RTI analysis demonstrated an interesting interaction of exposure phase by road type, where more RTIs were observed occurring on uncontrolled-access roadways in Phase 1. This result switched to more RTIs occurring on controlled-access roadways for Phases 2 and 3. While a fairly large percentage of RTIs still occurred on uncontrolled access roadways for Phases 2 and 3 (e.g., 43% and 39% respectively), this reversal may be indicative of driver adaptation changes in workload from driving with L2 systems on non-controlled access roadways versus controlled access roadways. Drivers may be adapting their perceived workload levels by road type in that their initial workload levels were too low for driving with L2 systems active on non-controlled access roadways. Drivers' workload levels while driving with L2 systems active on controlled access roadways may also have changed over time as they were more comfortable on controlled access roadways and thus began to receive more RTIs on these road types over time.

Limitations

There are several limitations that should be discussed regarding the above analyses. First, while two similar naturalistic driving data sets were used to perform these analyses, there were important differences between them. One key difference is that the inexperienced L2 drivers (L2 NDS) all drove one of five vehicle makes/models, whereas the experienced L2 drivers (VCC50 Elite NDS) drove 10 different vehicle makes/models. Thus, a wide variety of different L2 systems were evaluated across these two studies. While this makes these analyses fairly system-agnostic and representative of the variety of available L2 systems, the authors had to create some operational design domain constraints that were the same for all vehicle makes/models. For example, when calculating exposure to L2 systems, driving time over 40 mph was used as the cutoff for all makes and models regardless of whether a specific make/model allowed ACC or the lateral control system to be activated at a lower speed. Thus, our exposure metrics are not precise for all drivers. While the authors would argue that the consistency is more important than the few drivers with higher exposure between 35 and 40 mph, for example, readers should interpret these results understanding that these analyses are conservative regarding exposure and that some drivers in this sample had slightly higher exposures to L2 system activity.

With any NDS, the sample of drivers may have some inherent biases given the limited sample sizes (i.e., inexperienced L2 drivers [L2 NDS]: $N = 82$; experienced L2 drivers [VCC50 Elite NDS]: $N = 33$), as well as potential bias in the type of driver who may be willing to participate. In studies that investigate novel technologies, participants who may be less averse to new technology may be more willing to participate than others. How comfortable these participants were with technology is unknown. However, these technologies are new to the overall U.S. fleet. While some may argue that this introduces bias, early adopters represent drivers who are actually using these systems on our nation's roadways, making them a population important for study.

The analysis investigating secondary task engagement yielded notable results in that increased engagement of visual/manual tasks occurred over time when L2 systems were active. The measure of secondary task engagement over the duration of the matched sample was a simple yes/no. While this analysis was very interesting and useful, additional information regarding how long or for what duration of time drivers were willing to engage in visual/manual tasks while L2 systems were active versus available but inactive may be an even more important question.

The analyses presented in this report are highly focused on understanding how various driver behaviors change over time, as well as how drivers' willingness to engage L2 systems in various environmental conditions change over time. Because of this focus, it was discovered that our sample of drivers not only obtained different amounts of L2 system exposure, but they also accumulated L2 system exposure over different time periods (thus the introduction of the L2 Activation Group). This systematic difference in our participants played a role in the analyses for speed selection behaviors. Indeed, there could be other systematic differences among these participants. However, robust statistical models that account for individual differences among the participants were used to allieviate as many of these potential differences as possible.

A variety of metrics were used in this analysis, which is indicative of the power of NDSs to yield a wide variety of driver behavior and performance metrics. This data can also provide in-depth detail and precision (e.g., video data allowing for data coders to code precise secondary task behaviors in detail over epochs lasting several seconds), but some details are harder to obtain. For example, a continuous measure of traffic density is not feasible. To account for traffic levels, matching criteria that include vehicle speed, TOD, and day of week (weekend versus weekday) can help account for general traffic patterns but are obviously less than a perfect representation of traffic density. To better understand the conditions under which drivers engage L2 systems, the video would need to be viewed and coded to provide a ranking of traffic density (typically the Levels of Service scale is used) as well as weather conditions and/or lighting conditions. This level of coding has not been done and was beyond the scope of this project.

These analyses represent one of the first evaluations and identification of driver adaptation to L2 systems. The method developed in this study for evaluating driver adaptation could be used in future evaluations of L2 systems to improve and develop designs that support safety on our nations roadways.

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Study 2: Older Driver Study

Introduction

Behavioral Adaptation for Older Drivers

While there are theoretical approaches to conceptualizing driver adaptation as noted above (e.g., *risk homeostasis*, Wilde, 1982a, 1982b; *risk allostasis*, Kinnear & Helman, 2010), there remain questions about how older drivers specifically can and do adapt to novel technologies in the driving environment. First, truly novel driver interface and vehicle control paradigms facilitating automation across a variety of dimensions are rapidly being introduced into the fleet. Second, as the population ages, the transportation system will be stressed. Both trends are in effect today and are expected to continue unabated for several decades to come, but the construct of adaptation is perhaps more complex with older drivers in that functional impairment may be increasing (see Antin et al., 2017) as older drivers are simultaneously striving to adapt to novel technological innovation. However, for many older drivers, such adaptation may take place over a shorter duration than the progression of significant functional impairment.

A few studies have examined this space. In a study focused on situational awareness in a simulated driving environment, Kaber et al. (2012) found that a group of older drivers (65–81) adapted to dynamic hazards with greater vehicle speed reduction than a group of middle-age drivers (18–25). Liang et al. (2020) used the naturalistic driving research paradigm to investigate older drivers' subjective adaptation to advanced vehicle systems (e.g., blind spot warning and adaptive cruise control) over 6 weeks. Weekly phone surveys failed to show much change in the older drivers' trust of the advanced systems: they generally started high and remained at that level. However, focus group discussions conducted after the conclusion of the driving portion of the study did reveal attitudinal adaptation to the technologies across several dimensions, including perceived safety benefits, confidence in the technology, and functionality.

Objectives

This chapter presents an analysis that used two naturalistic driving databases (the L2 NDS and Older Driver NDS) from previous studies to address these four objectives. The four research objectives defined for this study were:

> **Research Objective 1:** Evaluate adult and older driver strategies and behaviors for maintaining vehicle safety while using L2 systems over time.
>
> **Research Objective 2**: Determine what factors influence how adult and older drivers rely on, and adapt to, L2 systems.
>
> **Research Objective 3:** Determine whether there are relevant outcomes of adaptation and reliance upon L2 systems for adult and older drivers.
>
> **Research Objective 4:** Evaluate the lessons learned from adult and older drivers using L2 systems in vehicles.

Method

Older Driver NDS

Liang et al. (2019) conducted an NDS with 18 older drivers (70–79). Participants drove one of four vehicles equipped with both lateral and longitudinal control systems (L2 technology) for 6 weeks each. The vehicles included in this study were the same as those included in the L2 NDS study (with the exception of the Tesla; Russell et al., 2018). For more detailed information on the vehicle models used in this study as well as the lateral and longitudinal automated driving features for each vehicle model, please refer to Appendix A. Participants were eligible for the study if they had not owned or regularly driven a vehicle that had either lateral or longitudinal control systems.

Except where explicitly noted, all analytical methods described in Study 1 above were employed in Study 2.

Older Driver NDS Sampling

Determining Exposure to L2 Automated Driving Systems

The first task involved gathering data on the amount of L2 exposure observed across drivers in the Older Driver NDS (Liang et al., 2020). L2 exposure was obtained for the older drivers using a machine-vision algorithm for experienced L2 drivers in the VCC50 Elite NDS study (Dunn et al., 2019).

The machine-vision algorithm used a camera view of the instrument panel to determine longitudinal and lateral system status (e.g., active, available but inactive, or unavailable). The machine-vision algorithm was trained to recognize the presence and status of the icons in the instrument panel that corresponded to the operating state of the L2 systems. A unique model was developed for each of the four vehicle models used in the Older Driver NDS. Once the algorithm was trained, and the video data processed, the system state was continuously available for the entire dataset within a certain degree of reliability. There were periods in time when the machine-vision algorithm was not able to reliably assess system state due to factors such as sunlight glare and malfunctions of the data acquisition system. To account for these periods of time, a reliability or an internal confidence metric was continuously calculated so that these periods of time could be removed from the analyses.

Using the output of the machine vision processing, a sampling approach similar to the one designed for the L2 NDS dataset was employed. This approach was stratified based on duration of L2 exposure (i.e., four samples per hour falling within the immediate term; two samples per hour for hours 3 to 8 (earlier short term); and 1 sample per hour for hours 8 and above (later short term). These samples were randomly selected within these periods of time and matched with control samples selected during the same time periods when L2 systems were available but inactive.

Middle-Age Drivers (L2 NDS)

Data from the L2 NDS (Russell et al., 2018), as described in Study 1 above were also used in the comparison to the Older Driver NDS.

Sampling for Matched Samples

The research team implemented a sampling plan designed to determine if the older drivers adapted over time while using L2 systems, and to effectively address the four research objectives. Given that we are interested in identifying learning over time, the sampling plan was designed to best assess the earliest moments of exposure to the L2 systems (i.e., learning curve, as discussed in the introduction). This sampling plan was designed to over-sample the steepest section of this learning curve to evaluate how driver behavior changes during this critical time.

Cumulative exposure to L2 systems was used because each participant had a different number of hours of exposure when L2 automated driving features were active. The sampling rate was ultimately determined by optimizing the resources available for data coding of the 2,000 matched samples. The final matched sample dataset incorporated the matched samples coded from the original NHTSA L2 NDS project (Contract No DTNH22-14-D00328L, Task Order #1) as well as the additional 2,000 samples coded as part of this NHTSA contract.

Summary of Data Sources

This project involves the in-depth analyses of data from L2 NDS drivers over their first 4 weeks of driving (the immediate and short-term) to driving data from older drivers for the first 6 weeks of driving with L2 systems. The different time periods were used due to the differences in the durations of each original data collection. Additionally, the older drivers in the Older Driver NDS only reached a maximum of 2 hours of active L2 exposure. Therefore, the Older Driver NDS data was compared to the L2 NDS drivers for the immediate phase only.

L2 NDS participants were adult drivers ranging in age from 25 to 54 years who lived and commuted in the Washington, DC, area. Participants in the Older Driver NDS were residents of the Blacksburg, Virginia, and surrounding areas and ranged in age from 70 to 79. The dataset was still similar to the L2 NDS in that the vehicles driven by participants all overlapped with the L2 NDS dataset vehicles. Although there may be an effect of different driving conditions (i.e., potentially suburban conditions for the Older Driver NDS), this was accounted for in the analyses. Suburban versus urban conditions were coded, as were other roadway condition variables. A comparison of the two datasets is presented in Table 12.

Table 12. Older Driver NDS and L2 NDS Phase 1 Summaries

Data	Older Driver NDS (Phase 1)	L2 NDS (Phase 1)	L2 NDS (Total)
Total # of drivers	14	82	121
Total # of activation events	130	2,307	8,419
Total # of available events	209	2,425	8,688
Total # of trips	370	3,521	10,505

Results

The following analyses are organized by research objective and specific research question supporting each objective. Given the low amount of driving time and small number of participants with usable data in the Older Driver NDS, many of the analyses below will be descriptive. If inferential statistical tests were conducted, these are described, and the test statistics presented.

To provide an overview of these two datasets, the total driving time was shorter for older drivers (Older Driver NDS) than middle-age drivers (L2 NDS). Six of the 14 drivers in this study had less than 400 minutes of total driving time. The older driver with the longest driving duration (Older Driver NDS) drove for approximately 20 hours, whereas the middle-age driver (L2 NDS) with the longest total driving duration drove for over 70 hours. Histograms of total driving time by number participants in both studies are presented in Figure 49.

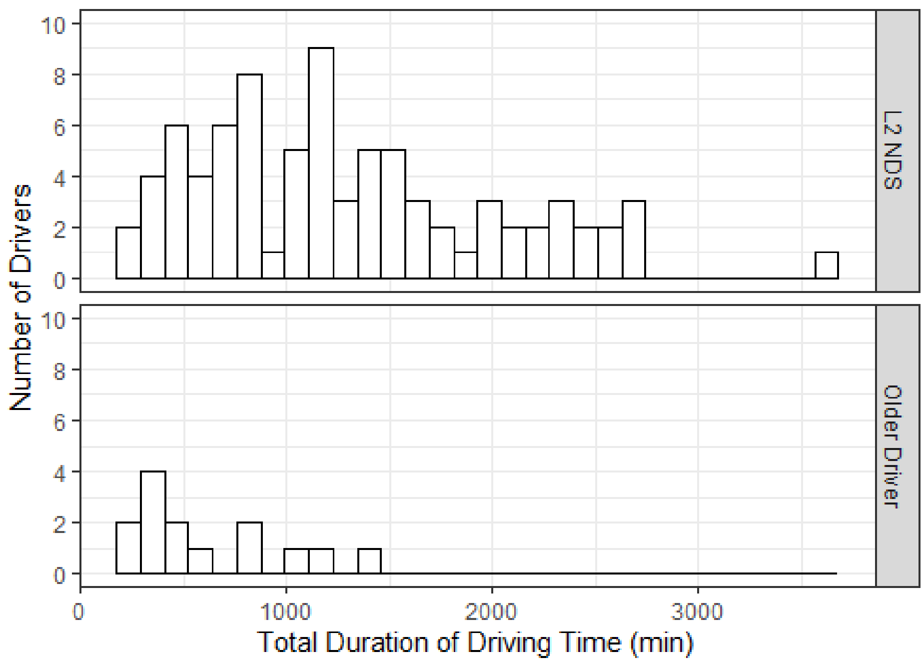


Figure 49. Distribution of the number of participants by total driving time for middle-age drivers (L2 NDS; top) and older drivers (Older Driver NDS; bottom)

L2 exposure showed a similar pattern. Figure 50 displays a histogram of the total duration of active L2 use for older (Older Driver NDS) and middle-age (L2 NDS; immediate phase only) drivers. The maximum duration of active L2 exposure for older drivers (Older Driver NDS) was less than 2 hours, whereas all middle-age drivers selected from the L2 NDS surpassed 3 hours of exposure. However, it is important to note that there were a few middle-age drivers in the original L2 NDS dataset with less than 3 hours of active L2 exposure; they were excluded from the analyses to maintain consistency in results across Study 1 and Study 2.

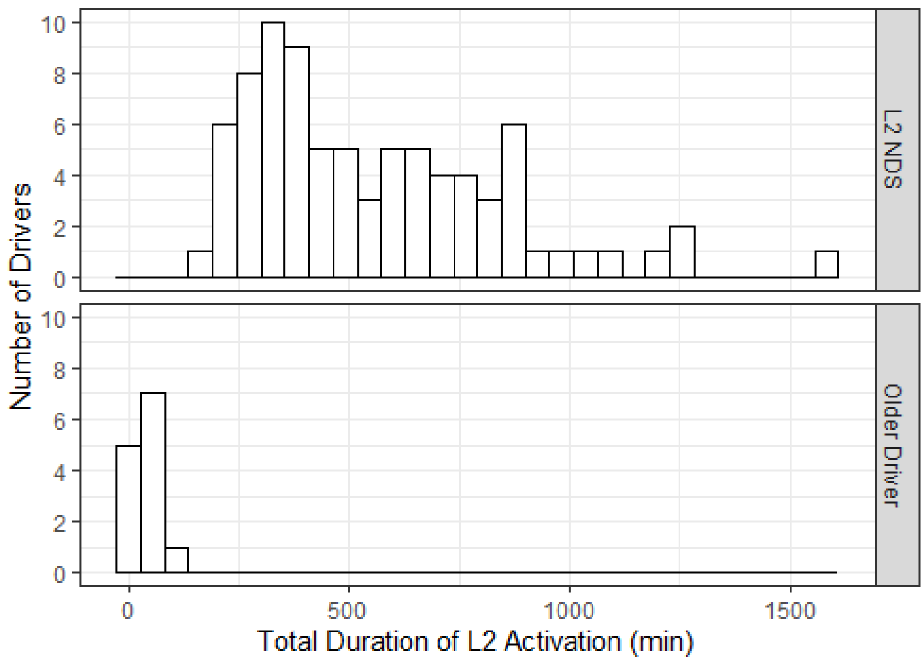
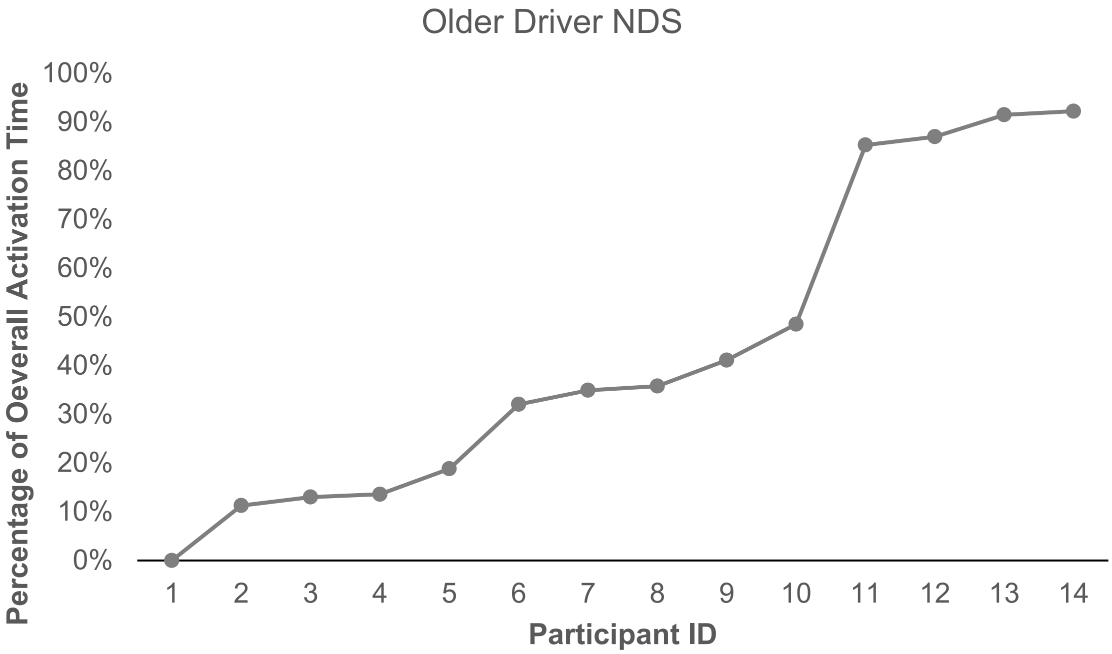


Figure 50. Distribution of the number of drivers by total driving time with L2 systems active for middle-age drivers (L2 NDS; top) and older drivers (Older Driver NDS; bottom)

Across both datasets, the duration of each individual L2 activation event was similar. In the Older Driver NDS, 90 percent of activations were shorter than 10 minutes, whereas in the immediate phase for middle-age drivers (L2 NDS), 99 percent of activations were shorter than 10 minutes.

The percentage of activation time was also calculated for each participant. This was calculated as the total duration of L2 activation time divided by the sum of the total duration of L2 active time plus the total duration of L2 available time (all selected from data that were above 40 mph only). Figure 51 displays the percentage of L2 activation time for older drivers (Older Driver NDS) and the middle-age drivers (L2 NDS). For older driver (Older Driver NDS; top panel), this percentage ranged from 0 to 99 with one participant out of 14 never activating L2 systems, whereas this percentage ranged from 13 to 100 among middle-age drivers (L2 NDS; bottom panel).



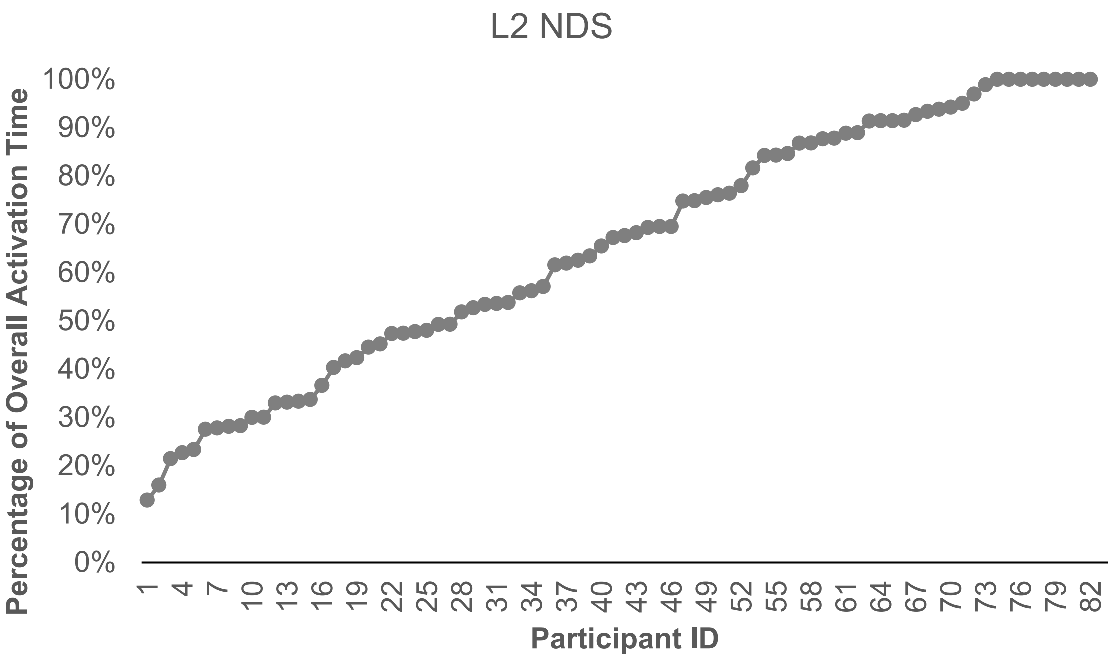


Figure 51. Percentage of L2 activation time for individual drivers (top: Older Driver NDS; bottom: L2 NDS)

Objective 1: Evaluate adult and older driver strategies and behaviors for maintaining vehicle safety while using L2 systems over time.

Driver Strategies

Speed Selection

To assess speed choice when activating L2 systems, each L2 activation performed by the driver was identified in the data. For each of these L2 system activations identified, data was recorded for each event, including vehicle speed at activation, GPS coordinates, and road type. Each L2 system feature activation was required to be at least 120 seconds in duration to ensure that the driver intentionally activated the L2 systems. Then, a random sample of matched controls was identified with the goal of a 1:1 match based upon driver identification number, TOD (± 4 hours), day of week (weekday versus weekend), and anytime the vehicle was traveling above 40 mph. Because some drivers had more driving time with L2 systems active events than L2 systems available but inactive, only 65 of the 130 L2 systems active events were able to be matched. Figure 52, below, displays the number of matched and unmatched events for each participant.

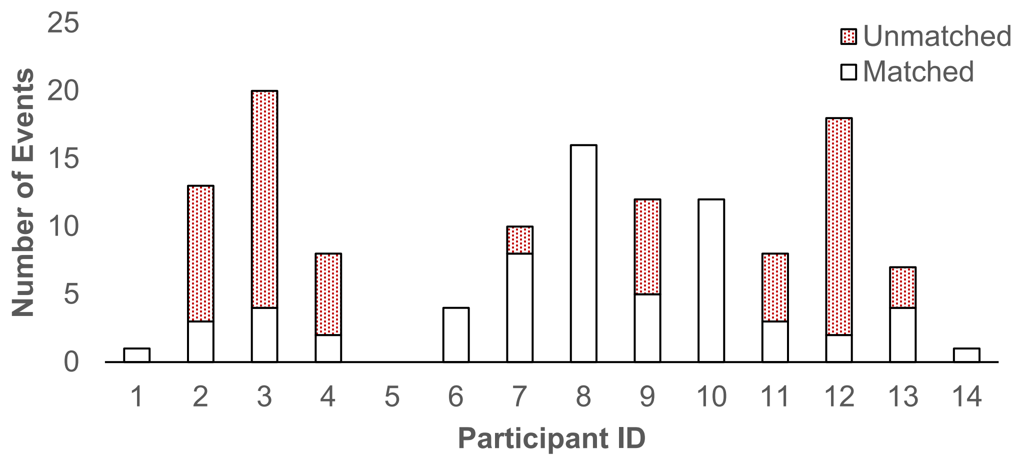


Figure 52. The number of L2 system activations where a matched control was identified (matched) and the number of L2 system activations where a matched control was unable to be identified (unmatched)

1. Do drivers tend to engage in speed selection above the speed limit during L2 activation compared to when L2 is available but inactive for the older (Older Driver NDS) and middle-age (L2 NDS) drivers?

Matched samples were used to assess speed selection above the speed limit when L2 systems were active versus available but inactive. The frequency of selecting speeds over the speed limit was significantly more common when L2 was active than when it was available but inactive for older drivers (Older Driver NDS). The speeding profiles are shown in Figure 53 as a histogram of the difference between speed limit and actual speed. Frequencies in each bin are plotted as a percentage of total events. Note that in these figures, the middle of the x-axis (zero) is representative of adhering to the speed limit, whereas bars to the right of zero indicate traveling faster than the speed limit and bars to the left of zero indicate traveling slower than the speed limit. Both L2 status, $F(1, 18{,}010) = 1{,}157.35$, $p < .001$, and driver groups, $F(1, 78) = 14.26$, $p <$

0.01, demonstrated statistical significance in speeding behaviors. When L2 systems were active, on average, drivers tended to select speeds which were 4.4 mph faster than the average speed driven when the L2 system was available but inactive. In addition, middle-age drivers (L2 NDS) tended to drive 5.2 mph on average faster than older drivers (Older Driver NDS).

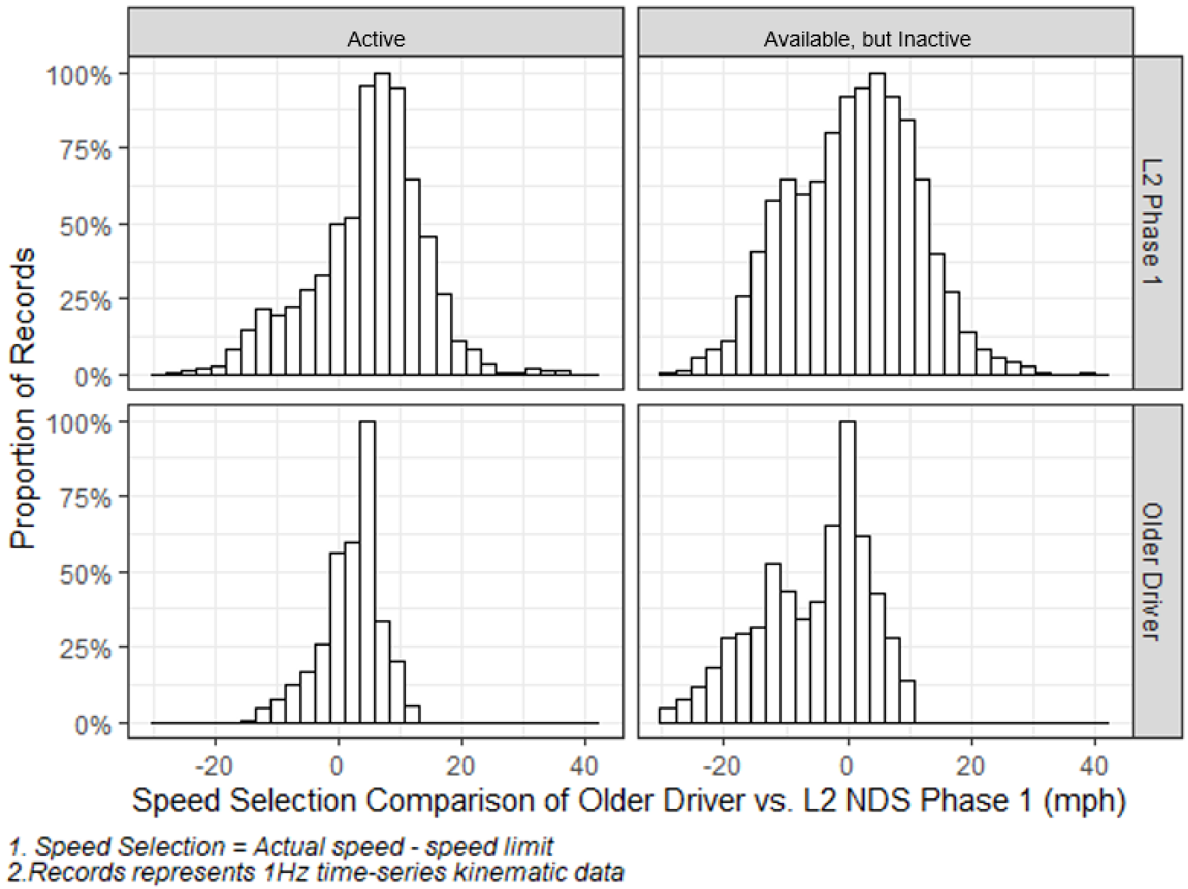


Figure 53. Histograms of speed selection profiles relation to speed limit comparison by L2 status and participant group (Older Driver versus L2 NDS Phase 1)

Driver Behavior

Do drivers look away from the roadway longer while using their L2 systems? How does this vary by phase?

There were several samples where eye-glances away from the forward roadway did not occur. This resulted in several values of zero in the dataset. The zeros were removed before analyzing these data to provide a clearer analysis of what eye-glance behavior looks like when it does occur. Eyes-off-road variables for all eye glances away from the forward roadway (i.e., longer than 0 s) are shown for both older (Older Driver NDS) and middle-age drivers (Phase 1 of the L2 NDS) in Figure 54. This figure displays four graphs of eye-glance data across both datasets for samples with L2 active and samples with L2 available but inactive for both the older (Older Driver NDS) and middle-age (L2 NDS) drives. ANOVA tests were used to analyze all four metrics of eye-glance data.

In Figure 54, total off-road glance duration is plotted in the top left panel. Results showed that older drivers (Older Driver NDS) had shorter total off-road glance duration than middle-age drivers (L2 NDS), both when L2 was active and when L2 was available but inactive. This was evidenced by a main effect of driver group, $F(1, 609) = 6.58$, $p = .01$. There was no significant main effect of whether L2 systems were active versus available but inactive on total glance duration ($F(1, 609) = 3.02$, $p = .083$). Mean off-road glance duration is plotted in the top right panel, and showed main effects of both L2 active, $F(1, 609) = 9.00$, $p = .03$, and driver age group, $F(1, 609) = 7.36$, $p = .07$. Overall, middle-age drivers (L2 NDS) had longer mean glance durations than older drivers (Older Driver NDS) drivers. Single longest off-road glance (bottom-left panel) showed main effects of both L2 active, $F(1, 609) = 8.44$, $p = .03$, and driver age group, $F(1, 609) = 4.845$, $p = .028$. This indicated that longest glances were longer overall when L2 was active for the middle-age (L2 NDS) drivers, but older drivers showed shorter longer glances than middle-age drivers. Finally, number of off-road glances showed a significant main effect of driver group, $F(1, 609) = 4.47$, $p = .035$, such that older drivers had fewer glances away from the forward roadway. There was no main effect of L2 active versus available but inactive ($F(1, 609) = .043$, $p = .835$). The assumption checks for these ANOVAs are presented in Figure 55 to Figure 58.

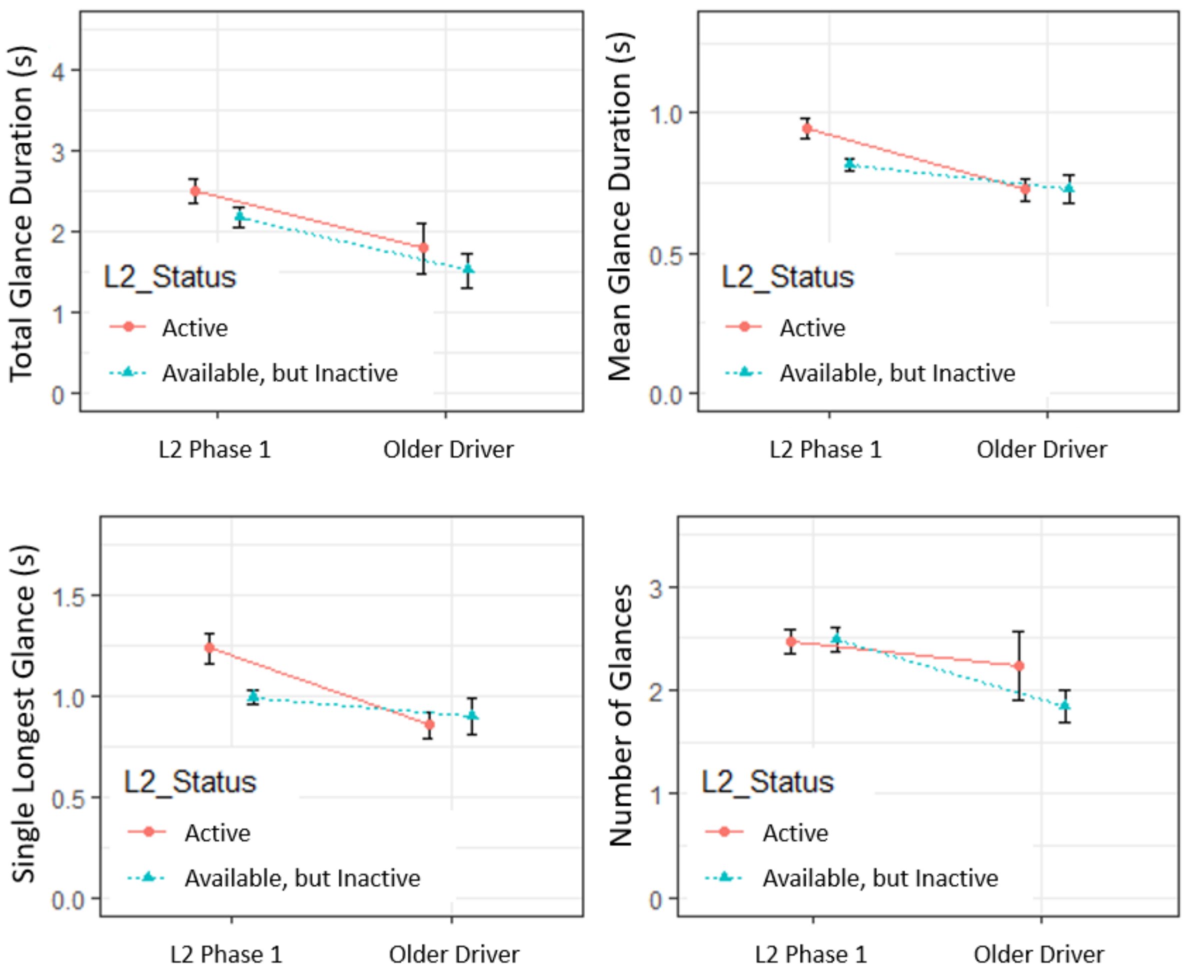


Figure 54. Eye glance metrics for older (Older Driver NDS) versus middle-age (L2 NDS Phase 1) drivers

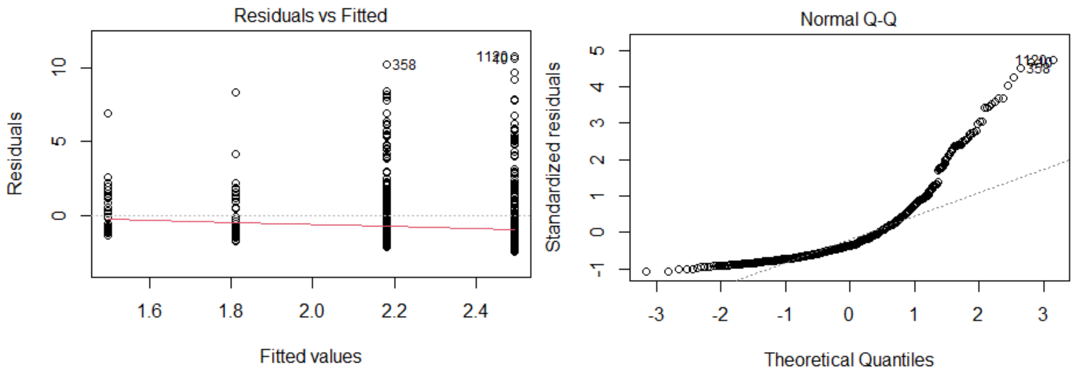


Figure 55. Assumption check for ANOVA (total glance duration)

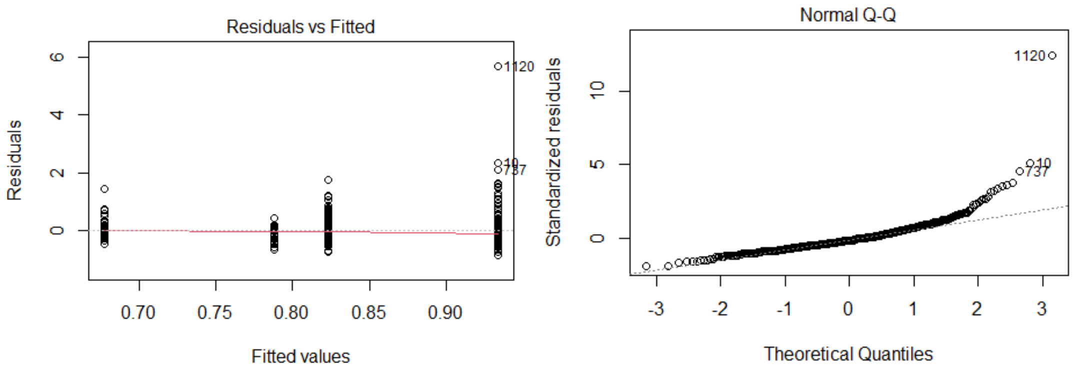


Figure 56. Assumption check for ANOVA (mean glance duration)

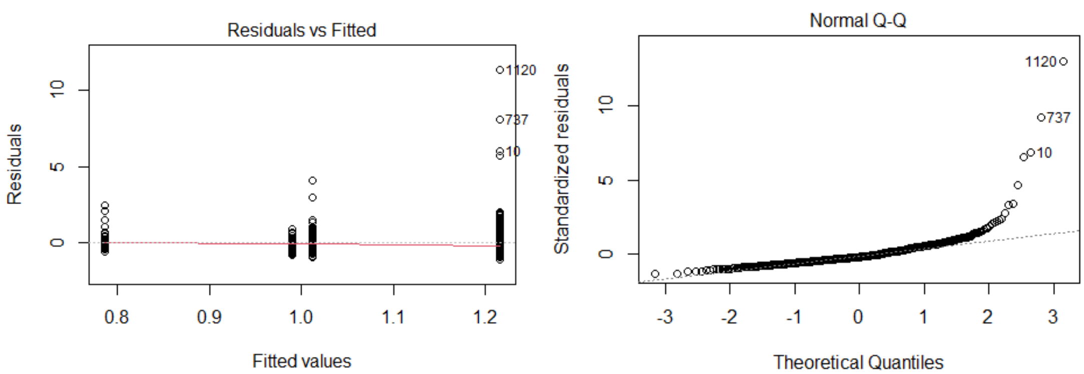


Figure 57. Assumption check for ANOVA (single longest glance duration)

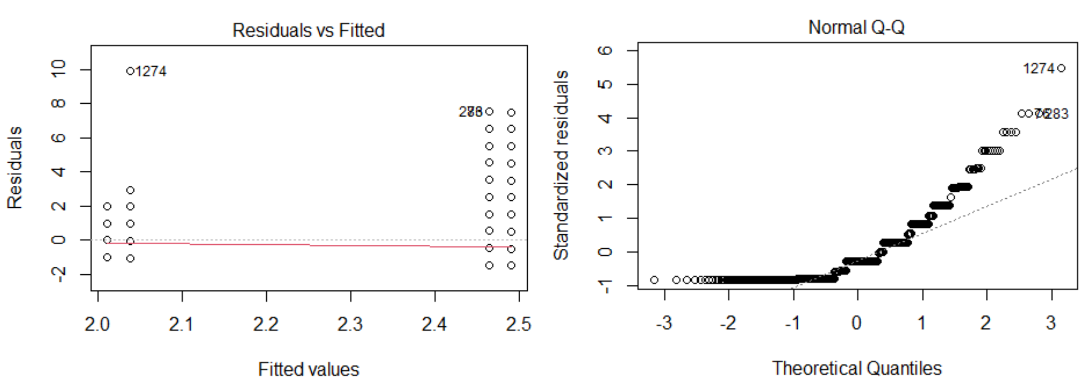


Figure 58. Assumption check for ANOVA (Number of glances)

Glances to the instrument cluster were also examined, but across all measures of eye-glances to the instrument cluster, no differences were detected between older (Older Driver NDS) and middle-age (L2 NDS) drivers or between L2 active or available but inactive status (total glance duration: $F(1, 718) = .02$, $p = .965$ for L2 active, and $F(1, 718) = 3.72$, $p = .054$ for participants; mean glance duration: $F(1, 718) = 0.08$, $p = .776$ for L2 active, and $F(1, 718) = 0.664$, $p = .415$ for participants; single longest glance: $F(1, 718) = 0.062$, $p = .804$ for L2 active, and $F(1, 718) = 0.54$, $p = .462$ for participants; number of glances: $F(1, 718) = .001$, $p = .97$ for L2 active, and $F(1, 718) = 2.56$, $p = .11$ for participants).

Secondary Task Engagement

Analyses for secondary task engagement were completed using the coded data where samples were randomly selected based upon whether L2 systems were active or available but inactive. Compared to the middle-age drivers (L2 NDS), older drivers were significantly less likely to engage in secondary tasks when L2 was active, χ^2 (1, N = 792) = 4.22, p = .04. There were five categories of distraction compared between the two datasets: visual, manual, visual/manual, cognitive, and no distraction. See Figure 59 for the percentage of each type of distraction observed in both datasets across L2 active and L2 available but inactive samples.

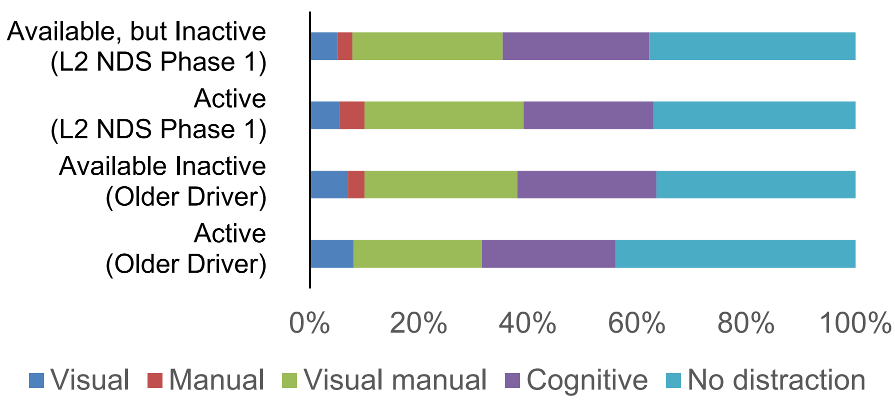


Figure 59. Secondary task distribution percentages comparison by L2 status and participant group (Older Driver versus L2 NDS Phase 1)

When secondary tasks were categorized by high-risk tasks, low-risk tasks, and no distraction (Table 7), the data showed a significant difference between the middle-age drivers (L2 NDS) and older drivers (Older Driver NDS) in the prevalence of high-risk secondary tasks. This difference was significant only for samples when L2 was available but inactive, χ^2 (1, N =792) = 4.57, p = .03 (χ^2 (1, N =792) = 3.32, p = .19 for L2 active case). These results are displayed in Figure 60, where the percentages of samples categorized as high risk, low risk, and no distraction are presented across both datasets and L2 status.

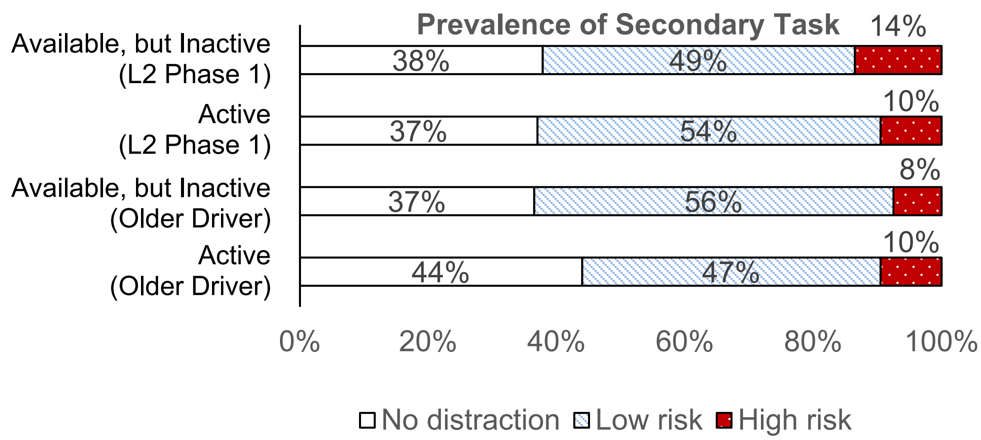


Figure 60. Percentage of matched samples where a high-risk secondary task, low-risk secondary task, or no distractions were observed for older (Older Driver NDS) and middle-age drivers (L2 NDS Phase 1)

Objective 2: Determine what factors influence how adult and older drivers rely on, and adapt to, L2 systems.

Exposure Analysis (Continuous Data)

What is the relationship of driving time when L2 systems are active versus when L2 systems are available but inactive for both older (Older Driver NDS) and middle-age (L2 NDS) drivers?

The pattern of L2 activation for older drivers (Older Driver NDS) is shown in Figure 61. This figure is a visual representation of how each participant accumulated their experience with L2 systems. Every vertical line segment represents L2 activation, and every horizontal line segment represents time driving with L2 systems available but inactive. Quadrant 1 (dotted lines) shows participants who accumulated L2 activation time more quickly (over a shorter duration of total driving time than the mean of 558 minutes). Quadrant 2 (solid lines) shows participants who accumulated L2 activation time more slowly (over a longer duration of total driving time than the mean). Generally, the figure demonstrates that drivers activated the L2 systems gradually over time. A similar plot with data from the L2 NDS drivers is available in the results section of Study 1 (Figure 29).

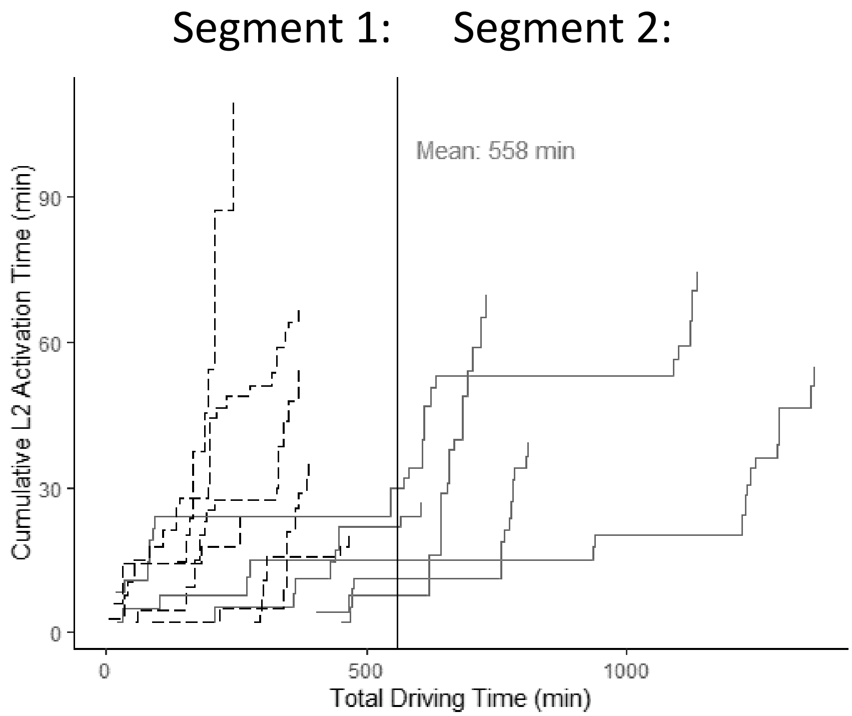


Figure 61. Older drivers (Older Driver NDS) total driving time by cumulative L2 activation time

Conditions Under Which Drivers Activated L2 Systems

The percentage of driving time with L2 active was used to compare the TOD and day of week (weekend versus weekday) when older drivers versus middle-age drivers (L2 NDS) chose to drive with L2 systems active. Percentages were calculated as the duration of active time divided by the sum of active driving time plus available but inactive driving time.

Time of Day

The ANOVA indicated no significant main effects for either driver type (Older Driver NDS or L2 NDS) or TOD ($F(1, 247) = 0.02$, $p = .897$ for driver type; and $F(6, 247) = 1.77$, $p = .107$ for TOD). Figure 62 displays the percentage of driving time under L2 activation for both datasets across TOD. The figure demonstrates that the older drivers did not have the opportunity to engage L2 systems at all during the very late hours (10 p.m. to 1 a.m.) or early morning hours (1 to 5 a.m.; 5 to 8 a.m.) because they did not drive during those time periods (no data points). The middle-age drivers (L2 NDS) did drive and did engage during these time periods, with the exception of the hours of 1 to 5 a.m.

The assumption check for this ANOVA is shown in Figure 63.

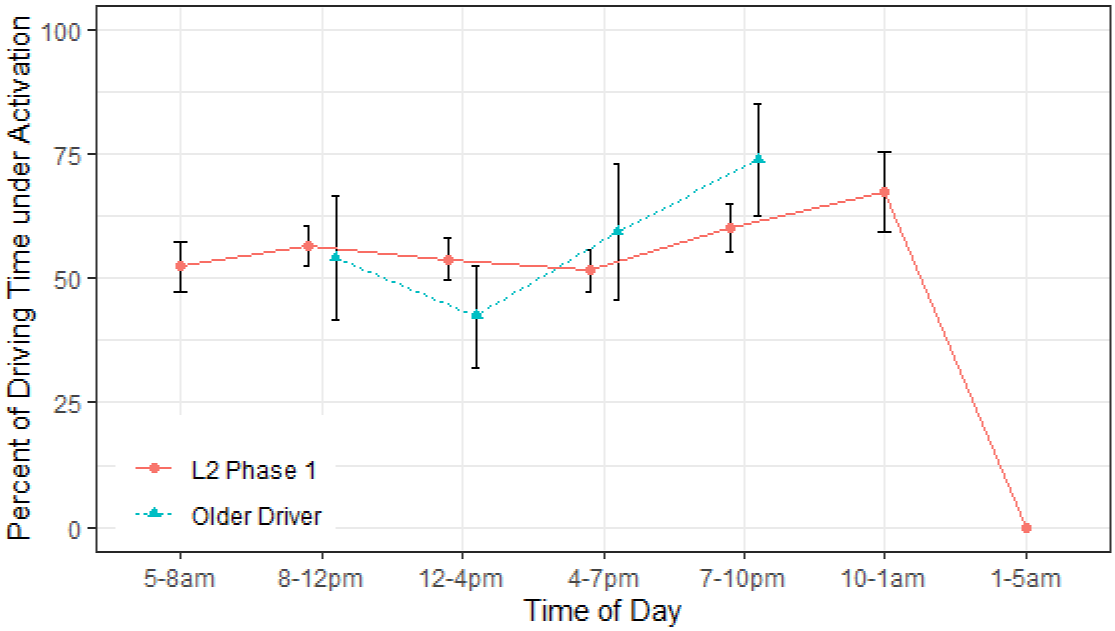


Figure 62. The percentage of driving time with L2 systems active for both older (Older Driver NDS) and middle-age (L2 NDS Phase 1) drivers by TOD

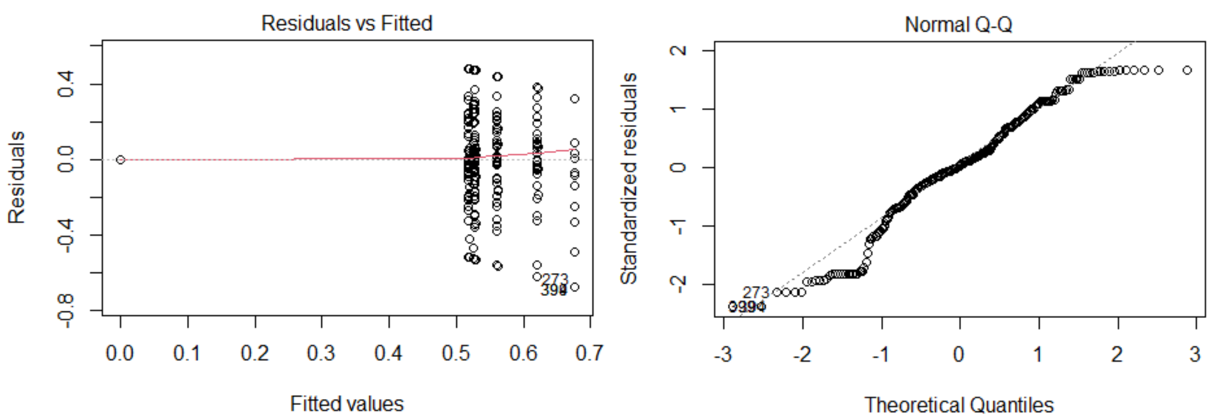


Figure 63. Assumption check for ANOVA in Figure 62

To put the above results into context, Figure 64 shows the percentage of total driving time by TOD for the first 3 hours of driving time for middle-age drivers (L2 NDS) and the older drivers (Older Driver NDS). Note that older drivers had a much higher percentage of their driving time in the middle of the day (12 p.m. to 4 p.m.), whereas the middle-age drivers were more evenly distributed throughout the day. Additionally, no driving data was collected between the hours of 1 a.m. and 5 a.m. and 5 and 8 a.m. for the older drivers. The total driving time for middle-age drivers in Phase 1 was 11,246 minutes across the 82 participants (1299.40 minutes, on average, per driver, with a standard deviation of 717.60 minutes), in comparison to the total driving time for older drivers, which was 528 minutes across 14 participants (62.0 minutes, on average, per driver, with a standard deviation of 371.00 minutes).

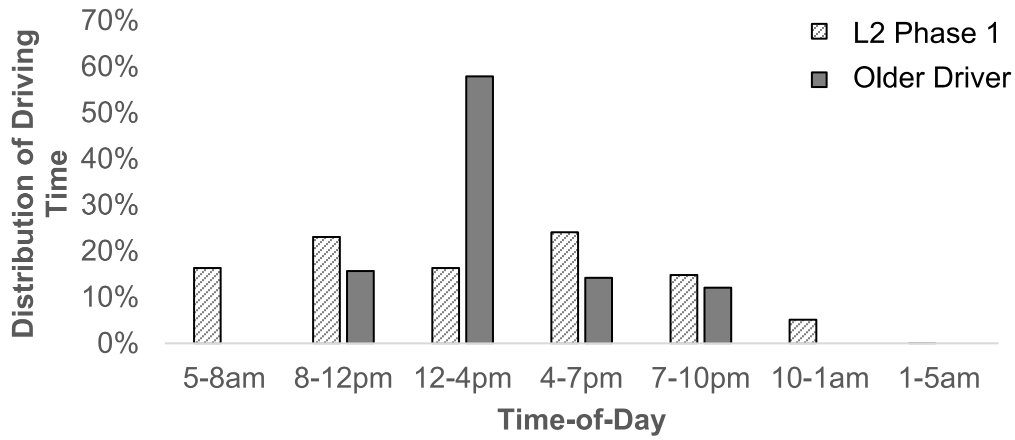


Figure 64. Distribution of total driving by TOD for older drivers and middle-age drivers

Day of Week (Weekday Versus Weekend)

An analysis was conducted to assess whether drivers engaged L2 systems more frequently during weekdays versus weekends. There were no significant differences for L2 activation by day of week for these two driver groups ($F(1,102) = .001$, $p = .977$ for day of week; $F(1,102) = 3.42$, $p = .067$ for driver group).

Road Type

The percentage of time with L2 systems active was also analyzed by road type. Figure 65 displays these results for older (Older Driver NDS) and middle-age (L2 NDS) drivers. All Class 1 roads (those with controlled access) were grouped together and are represented by the unfilled bars. All other road types (roads with uncontrolled access) were grouped together and are represented by the dotted bars.

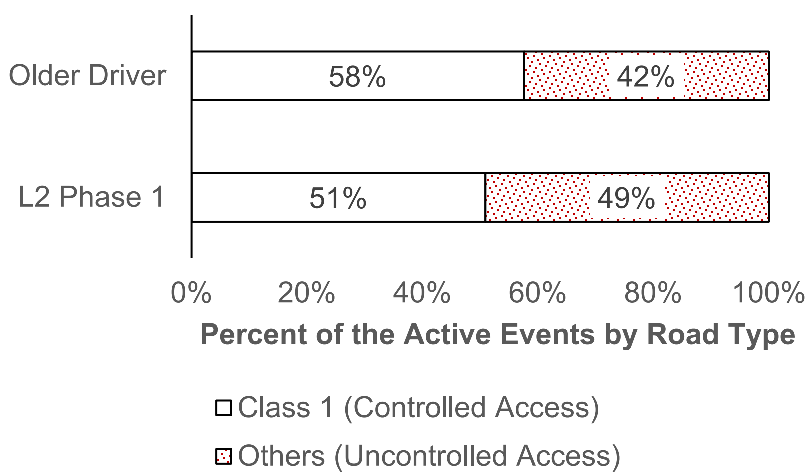


Figure 65. Percentage of events with L2 systems active by road type

No differences were observed between older and middle-age drivers based on a chi-square analysis, χ^2 (1, N = 2,430) = 1.77, p = .184, indicating that there was no statistically significant difference between the older and middle-age drivers in terms of activating the L2 systems on both controlled and uncontrolled access roadways.

Objective 3: Determine whether there are relevant outcomes of adaptation and reliance upon L2 systems for adult and older drivers.

Too few safety-critical events occurred in the Older Driver NDS to conduct meaningful analysis (i.e., only two near-crashes and one minor crash—a curb strike—occurred). A far greater source of driving data would be required to have sufficient numbers of safety-critical events for analysis. Additionally, there were no RTIs to assess for Older Driver NDS.

Objective 4: Evaluate the lessons learned from adult and older drivers using L2 systems in vehicles.

Older drivers demonstrated eyes-off-road glance patterns which were shorter in overall, mean, and longest-single glance duration, and older drivers looked away from the forward roadway less frequently in this study. From a transportation safety perspective, these results and conceptualizations present a conundrum. On the one hand, we might interpret the glance behaviors observed in this study as older drivers demonstrating generally greater caution and less distraction, perhaps based on their greater maturity, experience, and very low risk tolerance. However, research by Romoser and colleagues (2009) paints a different picture. Romser and colleagues (2009) have shown that older drivers scan less or have a narrower gaze dispersion in certain driving scenarios. Following on this work, researchers examined several underlying conditions which might explain why older drivers demonstrate a scanning deficit at intersections. These included head movement limitations, memory-related issues, and distractibility. However, they found that none of these fully explained the observed behavior. Instead, they determined that the propensity was, in effect, older drivers' conscious (or unconscious) attempts to adapt to their own perceived functional decrements. The fact that this behavior also had potentially maladaptive consequences (i.e., missed emergency cues outside of the direct forward view) was unknown to the older drivers (Romoser et al., 2013). In this study, an eyes-off-road glance was defined as one not directed to any of the following locations: forward, left window/mirror, left windshield, rearview mirror, right window/mirror, right windshield, or the instrument cluster. Thus, the phenomenon noted by Romoser and colleagues may have less of an impact on our currently reported results.

The secondary task analysis also indicates that older drivers behave more cautiously than their middle-age counterparts during L2 activation, demonstrating not only a lower percentage of visual and/or manual task time, but also a greater percentage of time with no secondary task of any kind. When the secondary tasks were broken out by low versus high risk, a pattern was less clear, as the older drivers engaged in low-risk tasks during L2 activation at a lower percentage than their middle-age counterparts; both groups engaged in high-risk tasks at the same percentage.

It should be noted that the designation of secondary tasks into low and high-risk categories is based on tasks and driving data observed or collected prior to vehicles being equipped with L2. While L2 technology may improve safety, the risk levels of specific secondary tasks while L2 is active must be investigated empirically.

Neither TOD nor road type was found to have any appreciable impact on L2 activation. For example, regardless of TOD, if the scenario encountered suggests that L2 activation can make driving easier, the driver may choose to activate the system. Regarding road type, middle-age drivers in our analysis produced very close to a 50-50 percent split of L2 activations across these two very different roadway configurations. The older drivers substantially favored controlled-access highways for L2 activations, but this did not rise to the level of statistical significance. It is possible that with a larger sample, this difference may persist and be found to be statistically significant.

One key lesson is that a sizable proportion of L2 activations take place on surface streets. It is difficult to know if the fact that these individuals were participating in a research study had an impact. Regardless, this finding highlights the importance of examining the context of activation and whether there are differential safety implications of L2 activation across these different contexts.

Not surprisingly, the older drivers in the current analyses did most of their driving in the early afternoon, with very little at night. Risk allostasis theory might predict that as drivers adapt to the perceived safety benefits afforded by the L2 automated systems, they may expand their comfort zone of driving contexts. For instance, many seniors might have been reluctant to drive at night due to age-related degradations typically seen in visual perception. L2 systems may increase their confidence in driving at night. However, it may take several months or longer of driving exposure to achieve such permanent changes in risk perception.

Conclusions

The analyses comparing older drivers' use and adaptation to L2 systems showed several key results. First, older drivers in the study chose to drive with L2 systems active much less frequently than the middle-age drivers. This may have been due to differences in the purpose of trips. The middle-age drivers were more often commuting into and out of a large metropolitan area and thus tended to drive more frequently even than adult commuters in more suburban/rural locations. This may also have been due to older drivers traveling less frequently on controlled-access roadways for a variety of reasons, although they were equally likely to activate L2 systems on both road types (i.e., the chi-square analysis of road type and driver group was not significant).

Evidence of driver adaptation to L2 systems may be seen most predominantly in the speed selection analysis. When the older drivers chose to engage L2 systems, their selected speed was above the speed limit more than the speeds driven when L2 systems were available, but inactive. This result may suggest that the L2 systems are simplifying their driving task to the point where they were willing to accept additional risk. The result may also be confounded by the possibility that drivers may be more likely to engage L2 systems when conditions are generally supportive of speeds higher than the posted limits (e.g., free-flowing controlled-access roads), although there were no significant effects of road type on L2 system use. Additionally, this effect was not observed in either eyes-off-road time or secondary task engagement, where no significant differences were observed between driving with L2 systems active as compared to when L2 systems were available, but inactive. Thus, it is unclear whether any driver adaptation was observed in these analyses. It is possible that behavioral adaptation to these technologies lasts several months, rather than weeks, especially as L2 systems may be used infrequently (i.e., on less frequent, longer trips, as opposed to much shorter daily errands).

The differences in L2 activation by TOD indicate that older drivers tend not to drive during late hours and thus there is no L2 activation during these time frames. Of greater interest are the differences observed during the 12 p.m. to 4 p.m. time frame, when the older drivers were not using L2 systems as frequently as middle-age drivers in the L2 NDS, versus between the hours of 7 and 10 p.m., when the older drivers were using the L2 systems more frequently than the middle-age drivers. Again, trip purpose during these time frames may play a role in these results. Older drivers may tend to drive on surface streets (to visit friends and shop) during the middle of the day, whereas when driving between 7 and 10 p.m., they may tend to be traveling longer distances. The opposite may be true for middle-age drivers.

Regardless, the results are useful in understanding how older drivers use these L2 systems during the first 2 hours of cumulative use. It is interesting how gradually most of these older drivers accumulated these 2 hours of L2 system use over the 6-week data collection period. Additionally, while older drivers did not tend to use L2 system for more than 10 minutes at a time, a similar result was found for the middle-age drivers. These results suggest that there are similarities in use across these two populations.

Overall, the results showed that older drivers: (1) used L2 systems, but not as frequently as other drivers; (2) tended to select speeds higher than the posted speed limit when L2 systems are engaged, similar to middle-age drivers; and (3) were willing to engage in high risk secondary tasks at similar rates as other adult drivers.

Limitations

Middle-age drivers (L2 NDS) were assumed to have little to no previous experience with L2 systems. This is an assumption, in that researchers knew that participants had never driven the make/model of the instrumented vehicle assigned to them for data collection, and thus the specific L2 systems were novel. It is unknown whether these participants owned vehicles with L2 systems. While the drivers in these two studies drove the same set of five vehicle make/models, there were subtle differences in how the various OEMs implemented the L2 technologies that were not directly tested or compared in these analyses.

The data was collected in different regions and driving environments. The middle-age drivers (L2 NDS) were commuters in the Washington, DC, area, whereas older drivers in the Older Driver NDS were residents of the Blacksburg, Virginia, a largely suburban area. Thus, the driving environments that these two sets of drivers negotiated were different, and it was impossible to control for this difference in the analyses. Another limitation worthy of consideration is that the Older Driver NDS included only 18 older drivers.

While stakeholders should be concerned about the greater degree of secondary task engagement during L2 usage observed in this study, it must be noted that without a robust analysis of safety-critical events (including crashes and near-crashes) in a much larger data collection, it is difficult to ascertain if such behaviors actually result in increased risk. That is, as predicted by risk allostasis theory, drivers may be adapting their behaviors to the driver assistance afforded by these advanced technologies.

General Discussion

This analysis used existing NDS data to evaluate whether driver adaptation occurred with the introduction of L2 systems. Three NDS databases were used: the L2 NDS, the VCC50 Elite NDS, and the Older Driver NDS. These three NDS databases provided varying levels of driver experience with L2 systems. L2 NDS and Older Driver NDS drivers were inexperienced L2 systems users, whereas the VCC50 Elite NDS drivers were experienced L2 systems users. Additionally, different driver age groups were also captured within these three NDS databases. Both inexperienced L2 drivers (L2 NDS) and experienced L2 drivers (VCC50 Elite NDS) ranged in age from 22 to 55 years of age, whereas Older Driver NDS drivers ranged in age from 70 to 79. Given these differences, Study 1 focused on drivers' experience with L2 systems (inexperienced L2 drivers versus experienced L2 drivers) and Study 2 focused on L2 system experience of middle-age drivers compared to older drivers. The same research objectives were evaluated for both studies.

An evaluation of driver behaviors and or strategies employed by drivers over time as they learn how to use L2 systems demonstrated that within hours of using L2 systems, drivers engaged in activities that may suggest that the driving task has gotten easier for them and that they are not necessarily performing their portion of the DDT (i.e., object event detection and response task) as required when using L2 systems. Experienced and inexperienced L2 drivers (VCC50 Elite NDS and L2 NDS) had longer eyes-off-road time and engaged in higher risk secondary tasks (i.e., tasks that required both visual and manual distraction) when L2 systems were engaged as compared to when L2 systems were available but inactive.

Additionally, the results of this study also found that drivers of both L2 experience levels and both driver age groups were selecting speeds above the speed limit when engaging L2 systems more frequently than when L2 systems were available but inactive. These higher speed selections will ultimately reduce the amount of time that drivers have to respond to traffic situations that may be unexpected.

These two general results may be of concern for traffic safety researchers and professionals regarding the use of L2 systems. It is important to note that this analysis was not a risk analysis and that while these behaviors (increased eyes-off-road time, high risk secondary task engagement, and speed selection above the speed limit) are considered unsafe behaviors in L0 and L1 Automated Driving System-equipped vehicles, it is currently unknown if these same behaviors are associated with crash occurrence with L2 automated features active.

Previous work has found no evidence of change in driver behavior when using L2 systems; however, these analyses were not focused specifically on an assessment of driver adaptation. The method used for this analysis was to over sample driver behavior based upon traditional learning curves. Given the steepness of the learning curve, we assumed that changes would occur more quickly in the initial hours of driving the L2-equipped vehicle. Thus, we oversampled in first 3 hours, moderately sampled through to 8 hours, and sampled less for driving after 8 hours of L2 system activation use. Using this strategy, the results indicated increases in the selection of speeds above the posted speed limit, eyes-off-road time, and high-risk secondary task engagement when L2 systems were active. These results support the hypotheses of the risk allostasis theory, in that drivers may find that as L2 systems take control of lateral and longitudinal control of the vehicle, drivers' workloads lighten and thus drivers may engage in activities that will increase their overall workload and risk, such as performing non-driving related secondary tasks or selecting speeds above the posted limits. This was a new method employed by the authors focused on understanding driver adaptation to new technologies.

References

AAA. (2019). *Advanced driver assistance technology names. AAA's recommendation for common naming of advanced safety systems*. www.aaa.com/AAA/common/AAR/files/ADAS-Technology-Names-Research-Report.pdf

Antin, J. F., Guo, F., Fang, Y., Dingus, T. A., Hankey, J. M., and Perez, M. A. (2017). The influence of functional health on seniors' driving risk. *Journal of Transport & Health*, *6*, 237-44. https://doi.org/10.1016/j.jth.2017.07.003

Bureau of Transportation Statistics. (2017). Average age of automobiles and trucks in operation in the United States. www.bts.gov/content/average-age-automobiles-and-trucks-operation-united-states

Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C. M., Lichty, M. G., Sanquist, T., Bacon, P., Woods, R., Li, H., Williams, D. N., & Morgan, J. (2016). *Human factors design guidance for driver-vehicle interfaces* (Report No. DOT HS 812 360). National Highway Traffic Safety Administration. www.nhtsa.gov/sites/nhtsa.gov/files/documents/812360_humanfactorsdesignguidance.pdf

Dunn, N., Dingus, T., & Soccolich, S. (2019). *Understanding the impact of technology: Do advanced driver assistance and semi-automated vehicle systems lead to improper driving behavior?* AAA Foundation for Traffic Safety.

Grove, K., Atwood, J., Hill, P., Fitch, G., Blanco, M., Guo, F., Russell, S., Marchese, M., Bartholomew, P., & Richards, T. (2016, June). Field study of heavy-vehicle crash avoidance systems. (Final report. Report No. DOT HS 812 280). National Highway Traffic Safety Administration. www.nhtsa.gov/sites/nhtsa.gov/files/812280_fieldstudyheavy-vehiclecas.pdf

Guo, F., Klauer, S. G., Fang, Y., Hankey, J. M., Antin, J. F., Perez, M. A., Lee, S. E., & Dingus, T. A. (2017). The effects of age on crash risk associated with driver distraction. *International Journal of Epidemiology, 46*(1), 258-265. https://doi.org/10.1093/ije/dyw234

He, D., & Donmez, B. (2019). Influence of driving experience on distraction engagement in automated vehicles. *Transportation Research Record, 2673*(9), 142-151. https://doi.org/10.1177/0361198119843476

Simons-Morton, B. G., Guo, F., Klauer, S. G., Ehsani, J. P., & Pradhan, A. K. (2014). Keep your eyes on the road: Young driver crash risk increases according to duration of distraction. *Journal of Adolescent Health, 54*, S61-S67.

Kinnear, N.A.D. & Helman, S. (2013). Updating risk allostasis theory to better understand behavioral adaptation. In M. Rudiin-Brown & S.L Jamson, (Eds.), *Behavioral adaptation and road safety.* CRC Press.

Klauer, S. G., Guo, F., Sudweeks, J. D., & Dingus, T. A. (2010). *An analysis of driver inattention using a case-crossover approach on 100-Car data* (Report No. DOT HS 811 334). National Highway Traffic Safety Administration. www.nhtsa.gov/sites/nhtsa.gov/files/811334.pdf

Klimoski, R., & Palmer, S. (1993). The ADA and the hiring process in organizations. *Consulting Psychology Journal: Practice and Research*, *45*(2), 10–36.

Kulmala, R., & Rämä, P. (2013). Definition of behavioural adaptation. In C. Rudin-Brown & S. Jamson (Eds.), *Behavioural adaptation and road safety* (pp. 18-36). CRC Press.

Liang, D., Lau, N., Baker, S., & Antin, J. F. (2020). Examining senior drivers' attitudes towards advanced driver assistance systems after naturalistic exposure. *Innovation in Aging*, *4*(3), 1-12. https://doi.org/10.1093/geroni/igaa017

Llaneras, R. E., Salinger, J., & Green, C. A. (2013). Human factors issues associated with limited ability autonomous driving systems: Drivers' allocation of visual attention to the forward roadway. *Proceedings of the Seventh International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design*, 92–98. https://pdfs.semanticscholar.org/344d/7759e45e059b9b73a0de25e7d8b4af52f5bb.pdf

Manser, M. P., Creaser, J., & Boyle, L. N. (2013). Behavioural adaptation: Methodological and measurement issues. In C. Rudin-Brown & S. Jamson (Eds.), *Behavioural adaptation and road safety*. CRC Press.

Manser, M. P., Ward, N. J., Kuge, N., & Boer, E. (2005, September 26-30). Driver behavioral adaptation in response to a novel haptic driver support system. *Human Factors and Ergonomics Society 49th Annual Meeting*, Orlando, FL.

Massaro, D. (1992). Broadening the domain of the fuzzy logical model of perception. In H. L. Pick, Jr., P. van den Broek, & D. C. Knill (Eds.), *Cognition: Conceptual and methodological issues* (pp. 51–84). American Psychological Association.

Newell, A. & Rosenbloom, P. S. (1980). Mechanisms of skill acquisition and the law of practice. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition*. Lawrence Erlbaum Asssociates.

Parasuraman, R., Molloy, R., & Singh, I. L. (1993). Performance consequences of automation induced "complacency." *The International Journal of Aviation Psychology*, *2*, 1–23. https://doi.org/10.1207/s15327108ijap0301_1

Romoser, M. R. E., & Fisher, D. L. (2009). The effect of active versus passive training strategies on improving older drivers' scanning in intersections. *Human Factors*, *51*(5), 652-68.

Romoser, M. R. E., Pollatsek, A., Fisher, D. L., and Williams, C. C. (2013). Comparing the glance patterns of older versus younger experienced drivers: Scanning for hazards while approaching and entering the intersection. *Transportation Research Part F: Traffic Psychology and Behaviour*, *16*, 104-16.

Russell, S. M., Blanco, M., Atwood, J., Schaudt, W. A., Fitchett, V. L., & Tidwell, S. (2018) Naturalistic study of Level 2 driving automation functions (Report No. DOT HS 812 642). National Highway Traffic Safety Administration. www.nhtsa.gov/sites/nhtsa.gov/files/documents/812642_naturalistic-study-of-level-2-driving-automation-functions.pdf

SAE International. (2021). *J3016 - Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles*.

Singh, I. L., Molloy, R., & Parasuraman, R. (1993a). Automation-induced “complacency”: Development of the complacency-potential rating scale. *International Journal of Aviation Psychology*, *3*(2), 111–122. https://doi.org/10.1207/s15327108ijap0302_2

Singh, I. L., Molloy, R., & Parasuraman, R. (1993b). Individual differences in monitoring failures of automation. *Journal of General Psychology*, *120*(3). https://search-proquest-com.ezproxy.lib.vt.edu/docview/1290594435/fulltextPDF/5C906DF5C8634684PQ/1?accountid=14826

Summala, H. (1988). Risk control is not risk adjustment: The zero-risk theory of driver behaviour and its implications. *Ergonomics*. https://doi.org/10.1080/00140138808966694

Taylor, D. H. (1964). Drivers’ galvanic skin response and the risk of accident. *Ergonomics*, *7*(4), 439-451.

Wilde, G. J. S. (1982a). Critical issues in risk homeostasis theory. *Risk Analysis, 2*(4), 249-258.

Wilde, G. J. S. (1982b). The theory of risk homeostasis: Implications for safety and health. *Risk Analysis, 2*(4), 209-225.

Appendix A: L2 Naturalistic Driving Study Vehicle Characteristics

Table 13. List of Vehicles From Each Dataset

Study	Vehicle	Number of Participants
L2 NDS	Audi Q7 2017	24
	Infiniti Q50 2015	24
	Mercedes E 350 2016	24
	Tesla Model S 2015	24 (23 included – over 1 hr L2 driving)
	Volvo XC90 2016 (Excluded)	24 (all excluded)
VCC50 Elite NDS	Tesla Model S 2015	3
	Tesla Model S 2016	8
	Tesla Model X 2017	1
	Acura MDX 2014	1
	Acura RDX 2016	2
	Acura TLX 2015	2
	Hyundai Genesis 2016	1
	Hyundai Genesis 2015	2
	Ford Fusion 2017	2
	Ford Fusion 2015	1
	Ford Fusion 2013	1
	Honda Accord 2017	2
	Honda Accord 2016	2
	Honda Civic 2016	1
	Mercedes CLS550 2012	1
	Volvo S90 2017	1
	Volvo XC90 2016	1
	Chrysler Pacifica 2017	2
	Chevrolet Suburban 2016	1
	Jeep Cherokee 2014	1
	Jeep Grand Cherokee 2015	1
	Hyundai Genesis 2012	1
	Hyundai Sonata 2016	2
	Hyundai Sonata 2015	1
	Ford Flex 2013	1
	Volkswagen Passat 2016	1
	Honda Accord 2015	1
	Cadillac SRX 2013	1
	Nissan Murano 2017	1
	Toyota Highlander 2016	3
	Toyota RAV4 2016	1
Older Driver NDS	Infiniti Q50 2015	5
	Volvo XC90 2016 (excluded)	4 (excluded)
	Mercedes E350 2016	5
	Audi Q7 2017	4

Table 14. Lateral and Longitudinal Control Feature Characteristics for Vehicles in the L2 NDS and Older Driver NDS Datasets

Vehicle Make & Model	Minimum Speed Lateral Control Feature Engages (mph)	Lateral Control Feature Engages Individually	Lateral Control Activation (Manual or Automatic)	Lateral Deactivation	Minimum Speed Longitudinal Control Feature Engages (mph)	Longitudinal Control Feature Engages Individually	Request to Intervene Source	Prompt	Separate Low Speed Features
2017 Audi Q7	40	Yes	Auto with/toggle button	Brake	20	Yes*	Hands on Wheel	No	Yes
2015 Infiniti Q50	45	Yes	Manual- Button	Brake	20	No	Lane Departure warning	No	No
2016 Mercedes E350	37	No	Manual- Lever	Brake	20	No	Hands on Wheel	Yes	Yes
2015 Tesla Model S	20	No	Manual- Lever	Brake or Steering Wheel	20	Yes	Hands on Wheel	Yes	Yes
2016 Volvo XC90	40	Yes	Auto-System Menu	Brake	20	Yes*	Hands on Wheel	Yes	Yes

*Although the longitudinal control feature can technically activate alone, this would only occur if a driver took additional steps to manually de-activate the lateral control feature.

Table 15. Lateral and Longitudinal Control Feature Characteristics for Vehicles in the VCC50 Elite NDS Datasets

			ACC		Lateral Control	
			Operating Speed		Operating Speed	
Vehicle Make/Model	**ACC**	**Lateral Control**	**Min.**	**Max.**	**Min.**	**Max.**
2014 Acura MDX [a]	X		25			
2015 Acura TLX [a]	X		25			
2016 Acura RDX [a]	X		25			
2016 Chevrolet Suburban	X	X	25		37	112
2017 Chrysler Pacifica	X	X	20		37	112
2015 Ford Fusion	X	X	16		40	
2017 Ford Fusion	X	X	16		40	
2015 Honda Accord [a]	X		22			
2016 Honda Accord [a]	X		25			
2016 Honda Civic [a]	X		25			
2017 Honda Accord [a]	X		25			
2015 Hyundai Genesis	X	X	20	110	40	110
2015 Hyundai Sonata	X		20	110		
2016 Hyundai Genesis	X	X	20	110	40	110
2016 Hyundai Sonata	X		20	110		
2014 Jeep Cherokee	X	X	20			
2012 Mercedes CLS500	X		20	120		
2015 Tesla Model S	X	X	18	90	35	90
2016 Tesla Model S	X	X	18	90	35	90
2017 Tesla Model X	X	X	18	90	35	90
2016 Toyota Highlander	X		25			
2016 Volkswagen Passat	X					

Appendix B: Eye-Glance Definitions

Table 16. Eye-Glance Location Definitions

Glance Location	Description	Definition of On/Off Road
Forward	Any glance in the direction of the vehicle's travel. Note that when the vehicle is turning, these glances may not be directed directly forward but towards the vehicle's predicted or intended heading.	On
Left Windshield	Any glance out the left portion of the windshield, to the left of forward (e.g., NOT looking in the direction of travel). Glances were coded only if clear, and finite. Left Windshield glances may be directed to vehicles ahead in the adjacent lane or other external distractions slightly ahead of the participant. These glances may also be taken while in the process of turning into or crossing a road (e.g., the vehicle is crossing through an intersection and the driver looks left and right to check traffic conditions).	On
Right Windshield	Any glance out the right portion of the windshield, to the right of forward (e.g., NOT looking in the direction of travel). Glances were coded only if clear, and finite. Right Windshield glances may be directed to vehicles ahead in the adjacent lane or other external distractions slightly ahead of the participant. These glances may also be taken while in the process of turning into or crossing a road (e.g., the vehicle is crossing through an intersection and the driver looks left and right to check traffic conditions).	On
Instrument Cluster	Any glance to the instrument cluster underneath the dashboard. This includes glances to the speedometer, control stalks, and steering wheel. Note that clusters may be in different places (e.g., driver-centerline versus vehicle-centerline), but they were included in this category regardless of location. In the case of trucks this includes an area that 'wraps' around the driver.	Off
Rearview Mirror	Any glance to the rearview mirror or equipment located around it. This category does not include any glances to the Center Stack.	On
Left Mirror	Any glance to the left-side mirror.	On
Right Mirror	Any glance to the right-side mirror.	On
Left Window	Any glance out the left-side window.	On
Right Window	Any glance out the right-side window.	On
Over-The-Shoulder (left or right)	Any glance over either of the participant's shoulders. In general, this will require the eyes to pass the B-pillar, but the eyes may not be visible.	Off
Center Stack	Any glance to the vehicle's center stack (the vertical portion), usually housing the radio, climate control, etc. Not to be confused with center console (cup holder area between driver and passenger).	Off

Glance Location	Description	Definition of On/Off Road
Mobile Phone (electronic communications device)	Any glance at a mobile phone or other electronic communications device (e.g., BlackBerry) or associated items (e.g., power cord, charger, etc.), no matter where they are located.	Off
iPod (or similar)	Any glance at an iPod or other personal digital music device, no matter where it is located	Off
Interior Object	Any glance to an identifiable object in the vehicle other than an electronic communications device or iPod. These objects include personal items brought in by the participant (e.g., purse, food, papers), any part of their body that they may look at (e.g., hand, ends of hair), other electronic devices (e.g., laptop), and also original-equipment-manufacturer-installed devices that don't fall into other categories (e.g., door lock, seat belt, window and seat controls). Glances to the center console (cup holder area between passenger seat and driver seat) are also included in this category. The object does not need to be in the camera view for a specific frame to be coded with this category. If it is clear from surrounding video that the participant is looking at the object, this category may be used. This category can be used regardless of whether the participant's hands are visible.	Off
Passenger	Any glance to a passenger, whether in front seat or rear seat of vehicle. Context is used (e.g., they are conversing) to determine this in some situations.	Off
No Video	Unable to complete eyeglance analysis because the face video view is unavailable. Used only when this condition is intermittent and surrounding syncs can be completed.	N/A
No Eyes Visible - Glance Location Unknown	Unable to complete glance analysis due to an inability to see the driver's eyes and face. Video data are present, but the driver's eyes and face are not visible due to an obstruction (e.g., visor, hand), or due to glare. This category was used when there was no way to tell whether the participant's eyes are on or off the road.	N/A
No Eyes Visible - Eyes Are Off-Road	Unable to determine specific glance location due to an inability to see the driver's eyes and face. However, it is clear that the participant is not looking at the roadway. Video is present, but the driver's eyes and face are not visible due to an obstruction (e.g., visor, hand), head position, or due to glare. Used when the eyes are not visible, but it is obvious that the eyes are not on the roadway.	N/A
Eyes Closed	Any time that the participant's eyes are closed outside of normal blinking (e.g., the participant is falling asleep). If the eyes are closed for five or more syncs (0.5s) during a slow blink, it is coded as Eyes Closed.	Off
Other	Any glance that cannot be categorized using the above codes (e.g., specific built-in vehicle features).	Off

Appendix C: Additional Analyses

Table 17. Logistic Regression for Any Secondary Task Engagement L2 NDS

Variables	**Est**	**LL**	**UL**	**Pr (>|z|)**
Intercept	1.998	1.517	2.630	<0.001
Available versus Active	0.898	0.692	1.165	0.416
0-3 versus 3-8 hours	1.083	0.791	1.483	0.619
0-3 versus 8+ hours	0.974	0.639	1.485	0.904
Darkness (lighted) versus Daylight	0.927	0.684	1.256	0.625
Darkness (not lighted) versus Daylight*	0.660	0.477	0.914	0.012
Dawn/Dusk versus Daylight*	0.542	0.334	0.882	0.014
Not divided (2-way) versus Divided*	1.535	1.052	2.238	0.026
One-way traffic versus Divided	0.867	0.578	1.299	0.489
Interaction: Available*PHASE 2	1.106	0.712	1.717	0.655
Interaction: Available*PHASE 3	1.113	0.646	1.915	0.700

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