Evaluation of Eyes Off Road During L2 Activation on Uncontrolled Access Roadways

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16. Abstract

The current study investigated eyes-off-road (EOR) behavior of drivers when traveling on uncontrolled access roadways in vehicles equipped with SAE Level 2 (L2) automated features. Previously collected naturalistic driving data were analyzed. Events were split between L2 features being active or available but inactive and matched across a spectrum of criteria (e.g., time of day). Primary analyses focused on L2 activation status and intersection type (no intersection, straight through intersection, and turning) and any interaction between those variables. EOR glances were operationalized in two ways: EOR 1, only forward was considered on road; and EOR 2, all driving-related glances were considered on road. EOR metrics involved total EOR, mean EOR, single longest glance, and number of glances per event. Overall, results for the primary research questions indicated that EOR behavior was higher when L2 was active across all EOR metrics, that intersection type affected EOR behavior on some metrics, and that there was an interaction between these variables for select metrics. Ancillary analyses represented differences for single longest glance when excluding slower speed segments, higher EOR behavior when speeds were below 37 mph, and increased hands-off-wheel behavior when L2 systems were active.

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Abstract

The current study investigated eyes-off-road (EOR) behavior of drivers when traveling on uncontrolled access roadways in vehicles equipped with SAE Level 2 (L2) automated features. Previously collected naturalistic driving data were analyzed. Events were split evenly between L2 features being active or available but inactive and matched across a spectrum of criteria (e.g., time of day). Primary analyses focused on L2 activation status and intersection type (no intersection, straight through intersection, and turning) and any interaction between those variables. EOR glances were operationalized in two ways: EOR 1, only forward was considered on road; and EOR 2, all driving-related glances were considered on road. EOR metrics involved total EOR, mean EOR, single longest glance, and number of glances per event. Overall, results for the primary research questions indicated that EOR behavior was higher when L2 was active across all EOR metrics, that intersection type affected EOR behavior on some metrics, and that there was an interaction between these variables for select metrics. Ancillary analyses represented differences for single longest glance when excluding slower speed segments, higher EOR behavior when speeds were below 37 mph, and increased hands-off-wheel behavior when L2 systems were active.

Acknowledgements

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Introduction

With the advent of advanced driver assistance systems (ADAS), the role of the driver is fundamentally changing; the driver support features may now perform portions of the dynamic driving tasks that are historically only performed by the driver. For example, adaptive cruise control (ACC) can control the speed of a vehicle by allowing the driver to set the speed at which the vehicle should travel as well as the driver's preferred following distance. Similarly, lane centering (LC)-type features control the lateral movement of a vehicle by keeping the vehicle in the middle of the lane while traveling on the roadway. While these features assist drivers with the lateral and longitudinal control portions of the dynamic driving task, they still require the driver to pay attention should something unexpected occur. Per the SAE International taxonomy for driving automation systems, Level 1 (L1) is defined as "the sustained and Operational Design Domain (ODD)-specific execution by a driving automation system of either the lateral or the longitudinal vehicle motion control subtask of the Dynamic Driving Task (but not both simultaneously) with the expectation that the driver performs the remainder of the dynamic driving task (DDT)" (SAE, 2021, p. 24. Level 2 (L2) is defined as "the sustained and ODD-specific execution by a driving automation system of both the lateral and longitudinal vehicle motion control subtasks of the DDT with the expectation that the driver completes the Object and Event Detection and Response (OEDR) subtask and supervises the driving automation system" (SAE, 2021, p. 24).

When introducing any new technology into a complex task environment (e.g., driving a motor vehicle), it is imperative to understand how users interact with the new technology and whether any unintended consequences may occur. The history of human factors has a multitude of examples where the deployment of a new technology is expected to yield a safety benefit, but the complexity of human behavior causes the net safety benefit to fail to meet expectations (e.g., center high mount stop lamps, or CHMSL; Kahane & Hertz, 1998). Thus, it is critical for human factors transportation researchers to perform in-depth analyses on human interactions with new technologies that will inform the design and deployment of these new technologies to realize the maximum safety benefit.

One potential driver behavior that may be problematic with L2 technologies includes driver's eye glance behavior. Klauer et al. (2012) found that eye glance durations of greater than 2 seconds out of 6 seconds increase crash/near-crash risk by 2 times that of an alert driver. Other researchers have found similar results using other naturalistic databases (Victor et al., 2015; Seppelt et al., 2017). Thus, if a driver's eyes-off-road (EOR) time increases when using L2 systems, this behavior may increase crash risk to a point where the safety benefits of these systems may be significantly reduced. Indeed, recent research shows that EOR behavior increases when automated systems are active (Dunn et al., 2021; Klauer et al., 2023; Noble et al., 2021).

Using existing L2 vehicle naturalistic driving databases, this research assessed whether drivers' eye glance patterns changed when using lateral and longitudinal control features while driving on uncontrolled roadway conditions (i.e., through intersections). Specifically, analyses compared the eye glance behavior of drivers with L2 systems active on uncontrolled access roadways to the same drivers without L2 systems active (i.e. manual driving) in the same roadway environments.

Objective

The goal of this research was to evaluate the eye glance patterns of drivers operating L2 vehicles (ACC + LC) during normal, baseline driving while negotiating surface streets. Driver's eye glance pattern was evaluated for 30-second periods when L2 systems were active as well as when the L2 systems were not active. The number of control segments per driver was stratified based upon hours traveled with L2 systems active on uncontrolled access roadways. Additionally, we reviewed the frequency of intersections of various types (signal, stop sign controlled, driver path through intersection) to ensure an appropriate sample.

Driver's glance patterns when L2 systems were active were compared to driver's glance patterns when L2 systems were not active while negotiating uncontrolled access roadways. Previous research found that EOR time increases crash risk (Klauer et al., 2006); thus, longer durations of EOR time when L2 systems are engaged may translate to higher crash rates for drivers engaging L2 systems. This analysis investigated the following specific research questions:

1. Do drivers have increased EOR time when L2 systems are active? Does intersection type influence this? Is an interaction present?
2. Do drivers take longer single glance durations when L2 systems are active? Does intersection type influence this? Is an interaction present?
3. Do drivers have longer average off-road glance duration when L2 systems are active? Does intersection type influence this? Is an interaction present?
4. Do drivers glance off road more frequently when L2 systems are active? Does intersection type influence this? Is an interaction present?
5. Does road type affect EOR behavior?

Method

Data were sampled from the Virginia Connected Corridor 50 Elite Vehicle Naturalistic Driving Study (VCC50 Elite NDS) dataset. This dataset contains data from 50 drivers of vehicles equipped with at least longitudinal control systems (ACC), although many vehicles also had some form of lateral control systems. The 50 participant drivers' personal vehicles were instrumented with VTTI-designed data acquisition systems similar to those used in other VTTI naturalistic driving studies. 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 12 drivers (eight male; four female; ages 32 to 68 [mean = 49.83, SD = 11.46]) were included for sampling. These drivers had Teslas equipped with ACC and some form of LC or lane keep assist (LKA). This Tesla sample consisted of 771 control segments (439 with L2 systems active/332 with L2 systems not active; see Table 1).

These control segments were identified based on the following criteria:

1. Speed 20 mph to 55 mph (upon approach to an intersection)
2. Intersection approach maneuver:
    a. Subject Vehicle going Straight through an Intersection
        i. Including 1) going straight on green; 2) going straight on two-way stop sign; 3) going straight on yield sign (consider merge ramps as going straight at yield; otherwise split between 1 and 2 options).
        ii. Including with and without lead vehicle (evenly split).
        iii. If without lead vehicle, the subject vehicle must NOT have stopped at the intersection due to a previous red light.
        iv. Vehicle should not stop as traveling through intersection.
    b. Subject Vehicle Turning at an Intersection
        i. Including 1) turning right on green; 2) turning left on green arrow; 3) turning left on green or flashing yellow; 4) turning left or right on yield sign (evenly split).
        ii. Including with and without lead vehicle (evenly split).
        iii. If without lead vehicle, for 1) and 2), the subject vehicle must NOT have stopped at the intersection due to a previous red light. For 3) and 4), it is all right if subject vehicle stopped due to cross traffic before proceeding.
    c. Subject Vehicle going Straight on Straight Road Segment (No Intersection)
        i. Including with and without lead vehicle.
        ii. Vehicle must not have stopped.

For the 771 epochs, a similar question reduction to the Second Strategic Highway Research Program Naturalistic Driving Study (SHRP 2 NDS) baseline sample was performed. This included coding various driver behaviors (e.g., secondary task, impairment) and environment and roadway variables. Additionally, 30 seconds of eye glance data were coded. Intersection type (i.e., straight road segment, traveling straight through an intersection, or turning through an intersection) was coded based on the final 6 seconds of the control segment.

Table 1. Distribution of Driving Epochs

L2 Status	Intersection Type: No Intersection	Intersection Type: Straight	Intersection Type: Turn	Total
Active	280	109	50	439
Not Active	226	50	56	332
Total	506	159	106	771

EOR Definitions

This project investigated two definitions of what were considered EOR behaviors during video reduction (see Table 2). The definitions are as follows:

Table 2. EOR Definitions and Glance Locations

EOR Definition	Glance Location: On Road	Glance Location: Off Road
EOR 1 – every glance is off road except toward the forward roadway	Forward	Left or right mirror/window/windshield Rearview Mirror Center Stack Instrument Cluster Eyes Closed Over-the-shoulder (left or right) Passenger Cell Phone Portable Media Device Interior Object
EOR 2 – all non-driving related glances are off road	Forward Left or right mirror/window/windshield Rearview Mirror Instrument Cluster	Center Stack Eyes Closed Over-the-shoulder (left or right) Passenger Cell Phone Portable Media Device Interior Object

Independent Variables

L2 Activation Status

- Active – Both ACC and LC were active during the segment.
- Not Active– Neither ACC nor LC were active during the segment.

Intersection Type

- No Intersection – Driver was traveling on a straight road segment with no intersection.
- Straight Intersection – Driver was traveling straight through an intersection.
- Turn Intersection – Driver was turning through an intersection.

Roadway Type

- Uncontrolled – Road segments that have uncontrolled access points (e.g., driveways, parking lot exits).
- Controlled – Road segments that have controlled access points (e.g., required merging from an on-ramp).

Dependent Variables

Total EOR Time (Seconds)

- The summation of EOR behavior during the driving epoch.

Mean EOR Time (Seconds)

- The average EOR time per each EOR instance (calculated as total EOR divided by the number of off-road glances).

Single Longest Glance (Seconds)

- The longest EOR glance for that driving epoch.

Number of Off-Road Glances (Frequency)

- The number of EOR glances for that driving epoch.

The analysis section of this report follows the investigated research questions mentioned above. It is important to note that each dependent variable was calculated using the EOR glance definitions defined in Table 2. For example, total EOR time (TEOR) was examined using EOR definition 1 and EOR definition 2, creating two TEOR metrics (TEOR_1 and TEOR_2).

Results

Various mixed-effect models were built to analyze the research questions. In all models, participants had more than one observation, which may affect model results. For this reason, driver ID was included in each model as a random effect.

RQ1: Do drivers have increased EOR time when L2 systems are active? Does intersection type influence this? Is an interaction present?

EOR time was examined using TEOR. A 2 x 3 analysis of variance (ANOVA) was used for this analysis by including L2 status (active/not active) and intersection (no intersection, straight intersection, turn intersection) as the independent variables, TEOR (continuous) as the dependent variable, and driver ID as a random effect. TEOR was calculated using EOR glance definitions 1 (TEOR_1) and 2 (TEOR_2). The main effect of L2 status was significant [$F(1, 766) = 26.21$, $p < .01$], suggesting drivers had increased TEOR_1 when systems were active ($M = 6.88$; $SE = 0.54$) compared to not active ($M = 4.58$; $SE = 0.53$). Further, the L2 status main effect was significant for TEOR_2 [$F(1, 766) = 21.48$, $p < .01$], suggesting drivers had increased TEOR_2 when systems were active ($M = 3.94$; $SE = 0.38$) versus not active ($M = 2.05$; $SE = 0.37$). For both glance definitions, this suggests that driver TEOR increases by approximately 2 seconds when L2 systems are active versus not active.

The main effect of intersection type was not significant for TEOR_1 [$F(2, 766) = 2.86$, $p = ns$]; however, it was significant for TEOR_2 [$F(2, 766) = 8.48$, $p < .01$]. Tukey post hoc comparison suggested that those driving through no intersection (straight road segment) had longer TEOR_2 ($M = 3.95$; $SE = 0.31$) than those traveling straight through an intersection ($M = 2.85$; $SE = .42$) and turning through an intersection ($M = 2.18$; $SE = .50$). This suggests that TEOR_2 decreases as drivers begin moving through intersections.

The interaction between L2 status and intersection was significant for TEOR_1 [$F(2, 766) = 4.16$, $p < .05$) but not TEOR_2 [$F(2, 766) = 2.83$, $p = ns$). Tukey pairwise comparisons revealed that when L2 systems were active, TEOR_1 was higher when traveling through no intersection or straight through an intersection (see Table 3). This suggests that when L2 systems were active, drivers only adjusted their EOR behavior when turning through an intersection (see Figure 1).

Table 3. Tukey Pairwise Comparison of L2 Status x Intersection for TEOR_1

Intersection	Status (I)	Status (J)	I – J	SE	*p*
None	Active	Not Active	2.89	0.47	<.01
Straight	Active	Not Active	3.72	0.79	<.01
Turn	Active	Not Active	0.31	0.94	ns

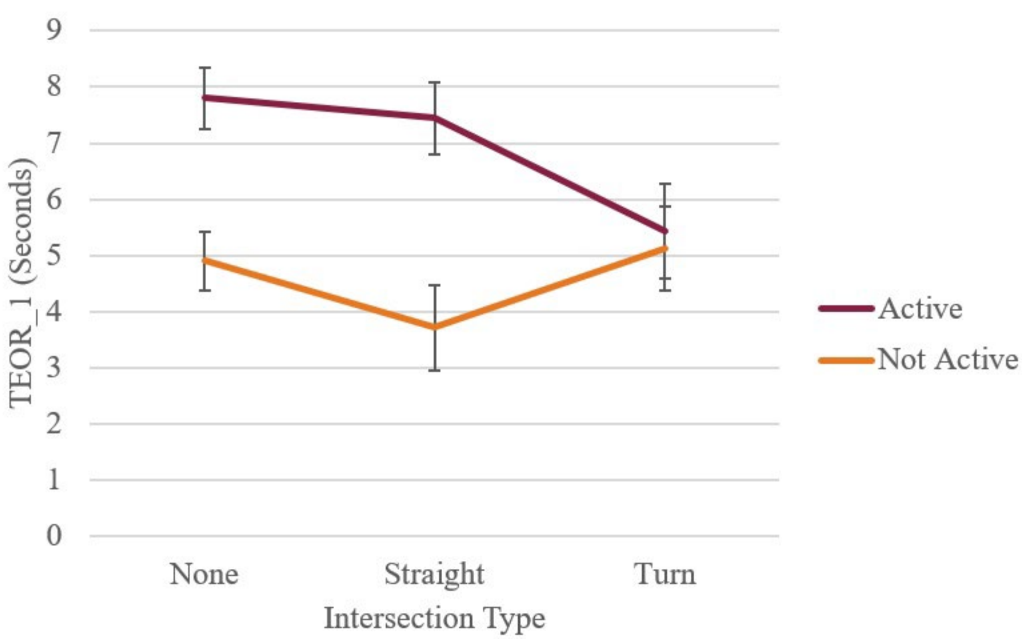

Figure 1. Graph. Examining the interaction of L2 Status x Intersection for TEOR_1.

RQ2: Do drivers take longer single glance durations when L2 systems are active? Does intersection type influence this? Is an interaction present?

EOR time was examined using the single longest off-road glance (SLG) per epoch. A 2 x 3 ANOVA was used for this analysis by including L2 status (active/not active) and intersection (no intersection, straight intersection, turn intersection) as the independent variables, SLG (continuous) as the dependent variable, and driver ID as a random effect. SLG was calculated using EOR glance definitions 1 (SLG_1) and 2 (SLG_2). The main effect of L2 status was significant [$F(1, 766) = 36.58$, $p < .001$], suggesting drivers had longer SLG_1 when L2 systems were active ($M = 1.79$; $SE = 0.12$) compared to not active ($M = 1.12$; $SE = 0.11$). Further, the L2 status main effect was significant for SLG_2 [$F(1, 766) = 35.37$, $p < .01$], suggesting drivers had increase SLG_2 when systems were active ($M = 1.39$; $SE = 0.10$) versus not active ($M = 0.73$; $SE = 0.10$). For both glance definitions, this suggests that drivers' SLGs are longer when L2 systems are active; however, these do not rise to the 2-second EOR time defined by Klauer et al. (2006).

The main effect of intersection type was not significant for SLG_1 [$F(2, 766) = 1.28$, $p = ns$]; however, it was significant for SLG_2 [$F(2, 766) = 3.19$, $p < .05$]. Tukey post hoc comparison suggested that those driving through no intersection (straight road segment) had longer SLG_2 ($M = 1.24$; $SE = 0.15$) than those traveling straight through an intersection ($M = 0.99$; $SE = .14$). No differences were found between no intersection or straight and turning. This suggests that SLG_2 decreases as drivers begin moving through intersections.

The interaction between L2 status and intersection was not significant for SLG_1 [$F(2, 766) = 0.49$, $p =$ ns) or SLG_2 [$F(2, 766) = 0.71$, $p = ns$).

RQ3: Do drivers have longer average off-road glance duration when L2 systems are active? Does intersection type influence this? Is an interaction present?

EOR time was examined using the mean eyes-off-road glance duration (MEOR). A 2 x 3 ANOVA was used for this analysis by including L2 status (active/not active) and intersection (no intersection, straight intersection, turn intersection) as the independent variables, MEOR (continuous) as the dependent variable, and driver ID as a random effect. MEOR was calculated using EOR glance definitions 1 (MEOR_1) and 2 (MEOR_2). The main effect of L2 status was significant [$F(1, 766) = 25.30$, $p < .01$], suggesting drivers had longer MEOR_1 when systems were active ($M = 0.90$; $SE = 0.04$) compared to not active ($M = 0.70$; $SE = 0.04$). Further, the L2 status main effect was significant for MEOR_2 [$F(1, 766) = 33.10$, $p < .001$], suggesting drivers had increased MEOR_2 when systems were active ($M = 0.88$; $SE = 0.05$) versus not active ($M = 0.56$; $SE = 0.05$). For both glance definitions, this suggests that driver MEOR time is longer when L2 systems are active compared to not active.

The main effect of intersection type was not significant for MEOR_1 [$F(2, 766) = 1.50$, $p = ns$] or MEOR_2 [$F(2, 766) = 3.01$, $p = ns$]. Further, the interaction between L2 status and intersection was not significant for MEOR_1 [$F(2, 766) = 0.17$, $p =$ ns) or MEOR_2 [$F(2, 766) = 0.52$, $p = ns$).

RQ4: Do drivers glance off road more frequently when L2 systems are active? Does intersection type influence this? Is an interaction present?

EOR time was examined using number of off-road glances (NOG). A 2 x 3 ANOVA was used for this analysis by including L2 status (active/not active) and intersection (no intersection, straight intersection, turn intersection) as the independent variables, NOG (continuous) as the dependent variable, and driver ID as a random effect. NOG was calculated using EOR glance definitions 1 (NOG_1) and 2 (NOG_2). The main effect of L2 status was significant [$F(1, 766) = 6.30$, $p < .05$], suggesting drivers had increased NOG_1 when systems were active ($M = 7.00$; $SE = 0.72$) compared to not active ($M = 5.94$; $SE = 0.71$). Further, the L2 status main effect was significant for NOG_2 [$F(1, 766) = 9.22$, $p < .01$], suggesting drivers had increased NOG_2 when systems were active ($M = 3.35$; $SE = 0.39$) versus not active ($M = 2.35$; $SE = 0.38$). For both glance definitions, this suggests that driver NOG increased when L2 systems were active versus not active.

The main effect of intersection type was not significant for NOG_1 [$F(2, 766) = 1.76$, $p = ns$]; however, it was significant for NOG_2 [$F(2, 766) = 11.71$, $p < .01$]. Tukey post hoc comparison suggested that those driving through no intersection (straight road segment) had increased NOG_2 ($M = 3.74$; $SE = 0.34$) compared to than those traveling straight through an intersection ($M = 2.69$; $SE = .41$) and turning through an intersection ($M = 2.12$; $SE = .47$). This suggests that NOG_2 decreased as drivers began moving through intersections.

The interaction between L2 status and intersection was significant for NOG_1 [$F(2, 766) = 6.03$, $p < .01$). Tukey pairwise comparisons revealed that when L2 systems were active, NOG_1 was higher when traveling through no intersection or straight through an intersection (see Table 4). This suggests that when L2 systems were active, drivers only adjusted their EOR behavior when turning through an intersection (see Figure 2).

Table 4. Tukey Pairwise Comparisons of L2 Status x Intersection for NOG_1

Intersection	Status (I)	Status (J)	I – J	SE	*p*
None	Active	Not Active	1.34	0.43	<.05
Straight	Active	Not Active	2.90	0.73	<.05
Turn	Active	Not Active	-1.07	0.87	ns

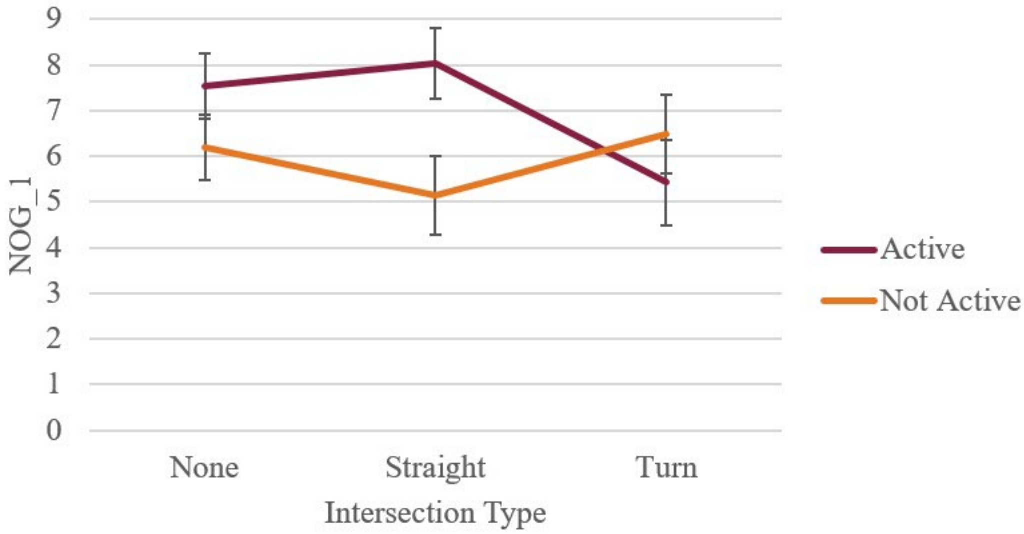

Figure 2. Graph. Examining the interaction between L2 Status x Intersection type for NOG_1.

The interaction between L2 status and intersection was also significant for NOG_2 [$F(2, 766) = 5.42$, $p < .01$). Tukey pairwise comparisons revealed that when L2 systems were active, NOG_2 was higher when traveling straight through an intersection (see Table 5). This suggests that when L2 systems were active, drivers only adjusted their EOR behavior when turning through an intersection (see Figure 3).

Table 5. Tukey Pairwise Comparison of L2 Status x Intersection for NOG_2

Intersection	Status (I)	Status (J)	I – J	SE	*p*
None	Active	Not Active	0.72	0.34	ns
Straight	Active	Not Active	2.48	0.57	<.05
Turn	Active	Not Active	-0.23	0.68	ns

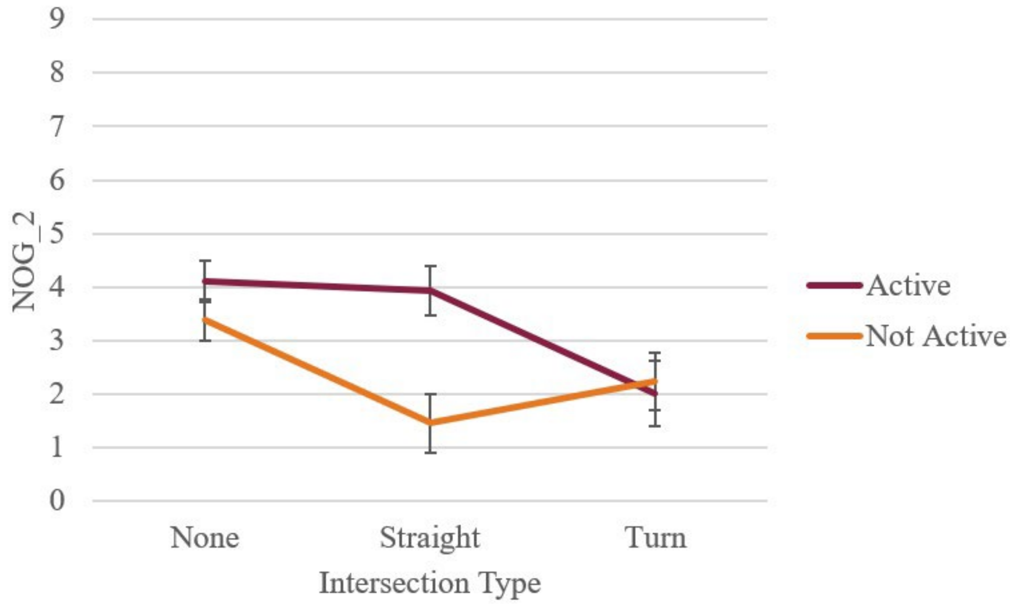

Figure 3. Graph. Examining the interaction between L2 Status x Intersection Type on NOG_2.

RQ5: Does road type affect EOR behavior?

The influence of road type on EOR behavior was examined by comparing EOR behavior on uncontrolled versus controlled-access roads. The uncontrolled epochs were the same 771 files examined in RQ1 through RQ4; 146 controlled segments were identified from the same 12 Tesla drivers as the uncontrolled epochs (82 when L2 systems were active; 64 when L2 systems were not active). Importantly, the uncontrolled epochs were 30 seconds long while the controlled were only 10 seconds. The uncontrolled epochs were adjusted by calculating EOR metrics for the final 10 seconds of each file to match the length of the controlled epochs.

EOR time was examined for each EOR metric and glance definition. A 2 x 2 ANOVA was used for these analyses by including L2 status (active/not active) and road type (uncontrolled/controlled) as the independent variables, EOR metrics (continuous) as the dependent variables, and driver ID as a random effect.

The main effects of each model are reviewed in Table 6. As with RQ1 through RQ4, when L2 systems were active, driver EOR time was higher across all EOR metrics. Regarding road type, the main effect was significant for TEOR_1, MEOR_1, and NOG_1 such that EOR behavior was higher when drivers were on controlled-access versus uncontrolled-access roadways. The interaction between L2 status and road type was only significant for TEOR_2 [$F(1, 913) = 4.26$, $p < .05$). Tukey pairwise comparisons revealed that when drivers were on controlled-access roadways, TEOR_2 was higher when L2 systems were active versus not active (see Table 7; Figure 4)

Table 6. Main Effects for the Various ANOVA Models

Independent Variables	TEOR_1 M(SE)	TEOR_2 M(SE)	MEOR_1 M(SE)	MEOR_2 M(SE)	SLG_1 M(SE)	SLG_2 M(SE)	NOG_1 M(SE)	NOG_2 M(SE)
L2 Status: Active	**2.57 (0.15)**	**1.42 (0.13)**	**0.80 (0.04)**	**0.56 (0.05)**	**1.17 (0.06)**	**0.76 (0.07)**	**2.95 (0.15)**	**1.44 (0.11)**
L2 Status: Not Active	1.80 (0.16)	0.80 (0.14)	0.59 (0.04)	0.39 (0.05)	0.80 (0.07)	0.47 (0.07)	2.43 (0.16)	0.93 (0.12)
Road Type: Uncontrolled	1.96 (0.18)	1.04 (0.10)	0.64 (0.03)	0.46 (0.04)	0.91 (0.05)	0.60 (0.06)	2.41 (0.12)	1.13 (0.08)
Road Type: Controlled	**2.42 (0.11)**	1.18 (0.16)	**0.76 (0.05)**	0.49 (0.05)	1.05 (0.08)	0.64 (0.08)	**2.97 (0.19)**	1.25 (0.14)

Note. Boldface indicates significant differences.

Table 7. Tukey Pairwise Comparison of L2 Status x Road Type for TEOR_2

Road Type	Status (I)	Status (J)	I – J	SE	*p*
Uncontrolled	Active	Not Active	0.30	0.14	ns
Controlled	Active	Not Active	0.95	0.29	<.05

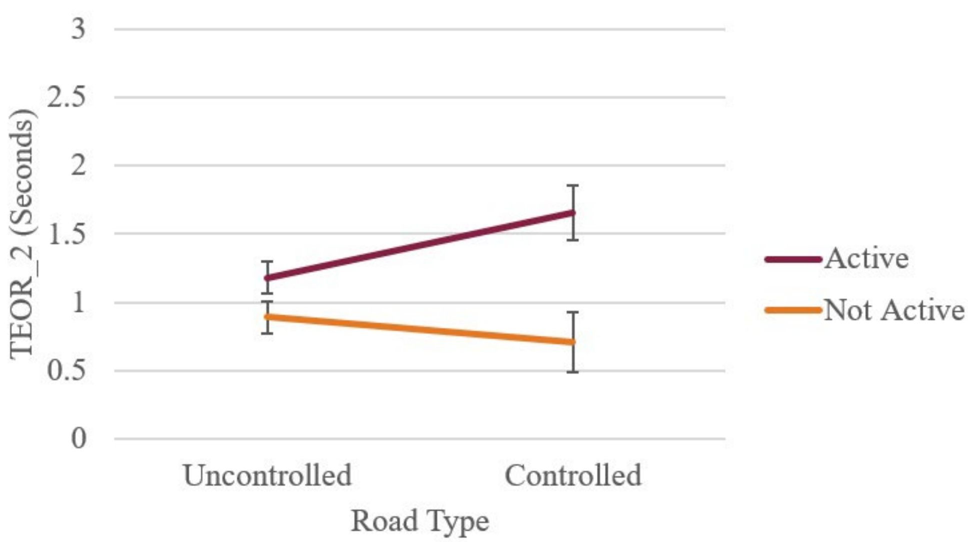

Figure 4. Graph. Examining the interaction between L2 status and road type for TEOR_2.

Ancillary Analyses

Additional analyses investigated the impact of slower speeds on the results by excluding segments when vehicle speed during an epoch was less than 0.5 mph. These analyses only investigated SLG_1 and SLG_2, as this EOR metric has been shown to be the most sensitive to change in a slow speed driving environment (Victor et al., 2015).

Identical models were used for these analyses as in RQ2. Results when excluding slower speed segments showed similar patterns for the L2 status main effect with SLG_1 [$F(1, 766) = 22.53$, $p < .01$] being higher with L2 active ($M = 1.56$; $SE = 0.07$) versus not active ($M = 1.11$; $SE = 0.07$).

This also held for SLG_2 [$F(1, 766) = 24.93$, $p < .01$] with L2 active ($M = 1.23$; $SE = 0.08$) being higher than not active ($M = 0.73$; $SE = 0.07$). As in RQ2, the intersection main effect was not significant for SLG_1 [$F(2, 766) = 0.16$, $p = ns$] but was for SLG_2 [$F(2, 766) = 4.79$, $p < .01$]. Importantly, the interaction between L2 status and intersection was significant for SLG_1 when excluding slower segments [$F(2, 766) = 3.22$, $p < .05$].

Additionally, analyses investigated whether overall speed affected model results. The average speed for all epochs was 42.96 miles per hour (mph); see Figure 5 for an overall speed distribution.

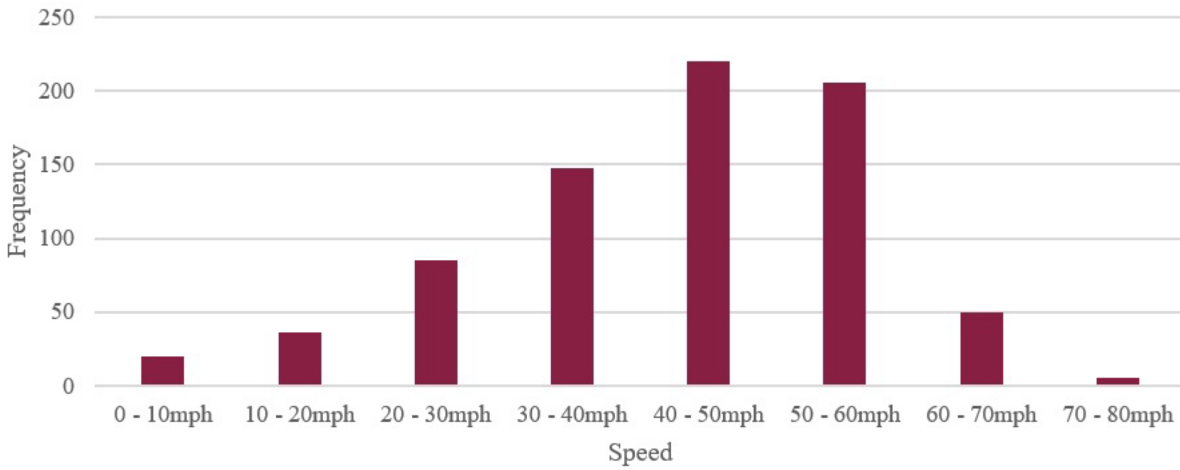

Figure 5. Graph. Speed distribution for the overall dataset.

Speed was included as a categorical factor in each research question model defined as the mean speed for each epoch categorized as under/over 37 mph. General Motors was interested in 37 mph as a threshold for proprietary reasons. No interactions were significant for all models. However, the main effect of speed was significant for MEOR_1 [$F(1, 766) = 4.45$, $p < .05$] and SLG_1 [$F(1, 766) = 4.18$, $p < .05$] such that EOR behavior was higher for both metrics when traveling below 37 mph (see Figure 6). This suggests that drivers' average EOR time was higher and their longest off-road glance was roughly one third of a second longer when traveling at slower speeds.

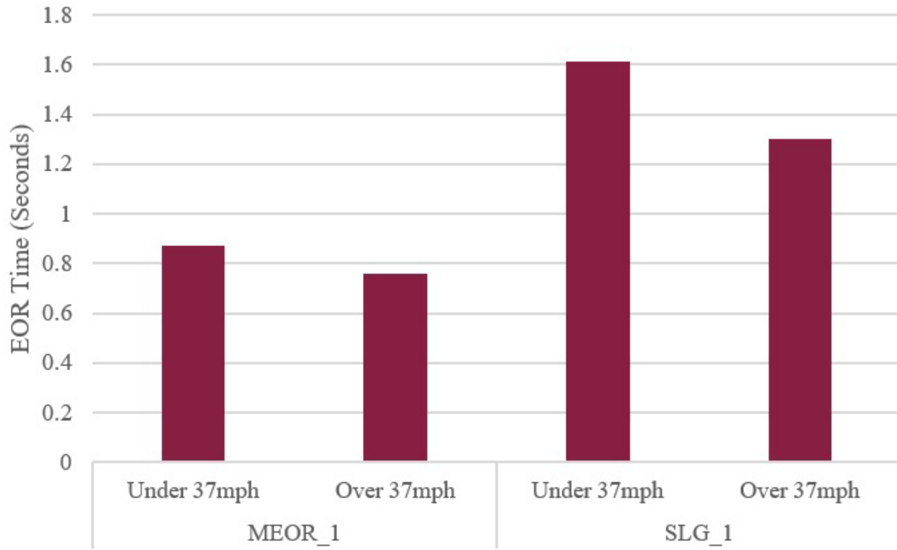

Figure 6. Graph. Examining EOR behavior when speeds are under/over 37 mph.

Secondary task type was also investigated for differences between L2 status. Secondary tasks were coded into one of three categories: cognitive, phone, or vehicle based. Full coding descriptions for each category are displayed in Table 8.

Table 8. Secondary Task Coding Description by Category

Cognitive	Phone	Vehicle
Child in rear/adjacent seat – interaction Passenger in rear/adjacent seat – interaction Talking/singing, audience unknown Phone – talking/listening, hands-free/hand-held	Phone – locating, reaching, answering, holding Dialing, hand-held device Browsing cell phone	Adjusting/monitoring instrument panel device Adjust/monitoring device integral to vehicle

Three hundred seventeen cognitive, phone, or vehicle secondary tasks were observed. Regarding L2 status, 185 secondary tasks were observed when systems were active and 132 when systems were not active. The odds of secondary task occurrence were not influenced by L2 status [odds ratio (OR) = 1.15; 95% confidence interval (CI): 0.85, 1.55]. Distribution of secondary task category across L2 status is provided in Figure 7.

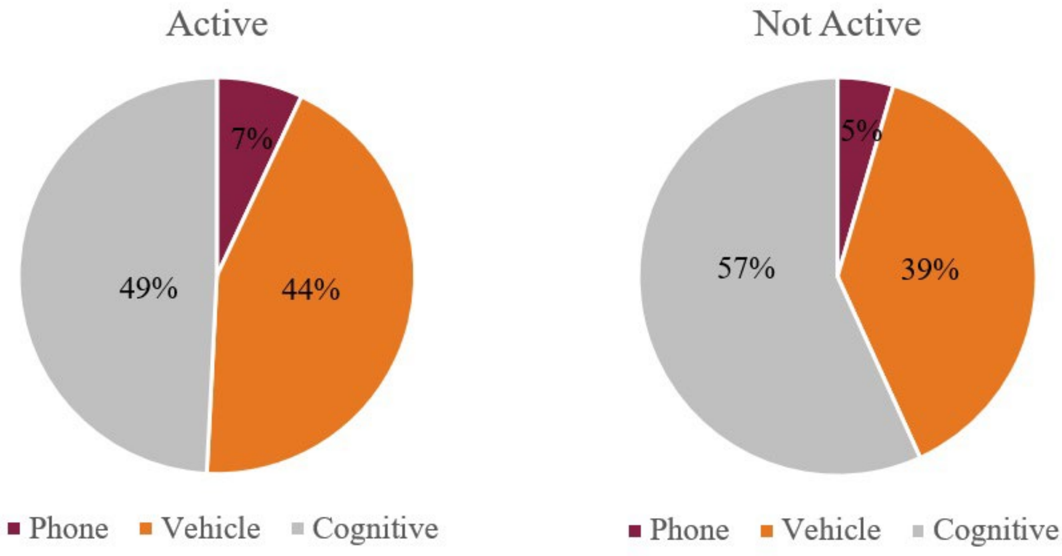

Figure 7. Graphs. Distribution of secondary task category by L2 status.

Hands-off-wheel behavior (HOW) was investigated for L2 status and intersection type. HOW was coded as “On” for both hands on the wheel, right hand (only, at least, off at least), and left hand (only, at least, off at least). “Off” was coded as none (arm or wrist only, fingers only, none). Overall, drivers had 3 times higher odds of HOW when L2 systems were active versus not active (OR = 3.05; 95% CI: 2.27, 4.12). Distribution of HOW for L2 status and intersection type is shown in Figure 8. Odds ratios for the various intersection types by L2 status can be found in Table 9.

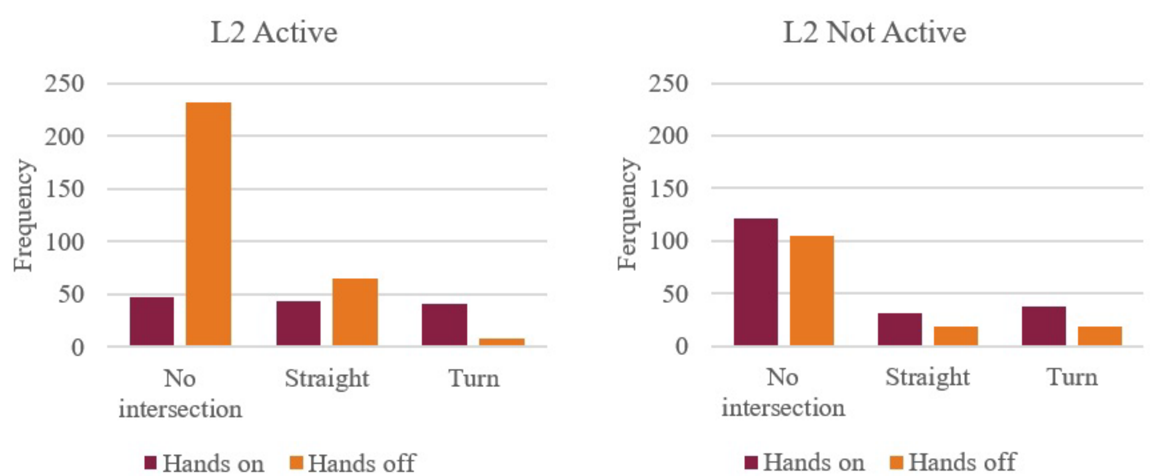

Figure 8. Graphs. HOW distributions among L2 status and intersection type.

Table 9. Odds Ratios for HOW for L2 Status and Intersection Type

	Active	Not Active	OR	CI Lower	CI Upper	*p*
No Intersection						
On	47	121	5.69	3.78	8.56	< .001
Off	232	105				
Straight						
On	44	31	2.41	1.21	4.79	< .05
Off	65	19				
Turn						
On	41	37	0.38	0.15	0.97	< .05
Off	8	19				

Note. Reference group was HOW "Off," exposure group was L2 "Active."

When traveling on a straight road segment with no intersection, HOW was nearly 6 times higher when L2 systems were active compared to not active. When traveling straight through an intersection, HOW was 2 times higher when L2 systems were active compared to not active. However, when turning through an intersection, odds of HOW were lower when systems were active compared to not active.

Discussion

The current study investigated EOR behavior among drivers of Teslas equipped with L2 automated lateral and longitudinal control. Overall, the results for the primary research questions indicated that EOR behavior was higher when L2 was active across all metrics, that intersection type affected EOR behavior on some metrics, and that there was an interaction between these variables for select metrics. Ancillary analyses represented differences for SLG when excluding slower speed segments, higher EOR behavior when speeds were below 37 mph, and increased HOW when L2 systems were active.

It is important to note the differences between each EOR glance definition (see Table 2). Definition 1 is more liberal in what is considered EOR behavior (i.e., only forward glances are considered on road), while definition 2 is more conservative (i.e., greater number of glances are considered on road). This provides two different viewpoints regarding EOR behavior; however, these differences should be considered when interpreting results. That is, the liberal nature of definition 1 could be argued to inflate EOR metrics based on the larger number of off-road glance classifications than definition 2.

The remainder of this discussion section will review results for each research question regarding main effects and interactions for each EOR metric, followed by a review of ancillary analyses.

L2 Status

EOR behavior was higher across all metrics when L2 systems were active. This pattern of higher EOR behavior with L2 active has been identified in previous research (Gaspar & Carney, 2019; Morando et al., 2021; Noble et al., 2021) and suggests that drivers are less attentive to the forward roadway when L2 systems are active. Although EOR metrics are higher for EOR definition 1 than definition 2, the differences in EOR metric between L2 active and not active remain relatively consistent across definitions (e.g., TEOR_1 and TEOR_2 both have ~2-second differences between active versus not active). All drivers were owners of Teslas, which operate under automation using Autopilot software. Notably, the software does not monitor driver glance behavior, nor do these vehicles have driver monitoring systems (DMS) to keep track of driver attention similar to other L2-equipped vehicles (e.g., General Motors Super Cruise). This lack of DMS or other glance behavior monitoring may contribute to increased EOR behavior.

Intersection Type

Unlike L2 status, the main effect of intersection type was only significant for certain EOR metrics. TEOR_2, SLG_2, and NOG_2 all had significant main effects for intersection type. For TEOR_2 and NOG_2, EOR behavior was higher when drivers were traveling through no intersection (straight road segment) than when traveling straight or turning through an intersection. For SLG_2, EOR behavior was higher when drivers were traveling through no intersection than straight through an intersection (the difference between no intersection and turn was not significant). Overall, this suggests that driver EOR behavior decreases for these select metrics as drivers begin moving through intersections. This could be due to the complications that intersections bring to the driving environment. That is, drivers modulate their eye glance behavior through intersections due to an increase in hazards such as bicyclists (Walker & Brosnan, 2007) or other vehicles (Lemonnier et al., 2015). The decrease in EOR behavior through intersections could also be attributed to older drivers having more driving experience and thus modulating their glance behavior in response to traffic conditions (Scott et al., 2013; Feng et al., 2019) or level of driving automation (Antin et al., 2023). Disparities between EOR definitions could have influenced results for intersection type, as EOR definition 1 includes glances to the left or right mirror/window/windshield as off road. This could inflate EOR time for turning—as drivers tend to look in the direction of travel when turning—and could explain why the intersection main effect is only significant for EOR 2 definitions.

Roadway Type

Differences between EOR behavior on controlled versus uncontrolled access roadways were investigated. The main effect of roadway type was significant for TEOR_1, MEOR_1, and NOG_1, suggesting that EOR behavior was higher for these metrics when drivers were on controlled-access roadways. Previous research shows that drivers tend to decrease their EOR behavior when the driving environment becomes more complex and demanding (Tivesten & Dozza, 2014; Risteska et al., 2021). Controlled-access roadways could be considered less demanding than uncontrolled, as uncontrolled-access roadways, by nature, have random entry points for ambient traffic (e.g., parking lots, personal driveways) or crosswalks with pedestrian interactions. Controlled-access roadways have designated areas (e.g., merge ramp) to anticipate ambient traffic entering their forward path of travel and no crosswalks to monitor.

Interactions

Interactions between intersection type and L2 status were significant for TEOR_1, NOG_1, and NOG_2. Differences between EOR definitions may explain why only TEOR_1 was significant among all other EOR metric definitions; however, both NOG definitions were significant, suggesting a clear interaction. Drivers seem to adjust their NOG behavior when they begin to move through intersections and L2 systems are not active (e.g., NOG drops from no intersection to moving straight through an intersection). However, when L2 systems are active, NOG modulation does not happen until turning through an intersection. The drop in NOG when systems are not active while moving straight through an intersection and lack of modulation when systems are active in the same context account for significant differences in the interaction. It has been shown in previous research that drivers using L2 systems adjust their EOR behavior according to the driving context (e.g., lead vehicle present; Morando et al., 2019). Traveling straight through an intersection involves less driver input than turning through an intersection (e.g., scanning off-axis path of travel). In addition, L2 systems control longitudinal and lateral vehicle controls, meaning if lead vehicles are not present, there is less for the driver to monitor even if they begin traveling straight through intersections. Lead vehicle presence did not affect research question models, and this, combined with the dynamic driving task requiring less of the driver, could explain why drivers only modulate NOG behavior when L2 systems are active and turning through an intersection.

Ancillary Analyses

When drivers were traveling at lower speeds, SLG_1 and MEOR_1 were higher when traveling below 37 mph on uncontrolled roadways as opposed to above. As referenced previously, drivers tend to modulate their EOR behavior as the driving environment becomes more complex and demanding (Tivesten & Dozza, 2014; Risteska et al., 2021). Uncontrolled roadways could be considered more demanding (e.g., parking lot exits, personal driveways); however, when combined with lower speeds, these roadway types could provide less perceived urgency for these hazards and lead to increased EOR behavior (Risteska et al., 2021). It is important to note that although the differences in SLG_1 and MEOR_1 were statistically significant, the small magnitude of this difference may limit the practicality of the result (e.g., only 0.11 seconds difference for MEOR_1).

Secondary task rates were numerically higher when L2 was active versus not active, but this was not a significant difference. This pattern is similar to previous research that suggests drivers are more willing to engage in secondary tasks when L2 systems are active (Llaneras et al., 2013; Naujoks et al., 2016; Noble et al., 2021).

Odds of HOW were shown to be 3 times more likely when L2 systems were active compared to not active. Further, when considering intersection type, drivers' HOW decreased as they began moving through intersections. This decrease could be due to the increased demand of the driving context causing the driver to be more attentive (Tivesten & Dozza, 2014; Risteska et al., 2021), even when automation is active. It is important to note that all study vehicles were Teslas. Tesla requires drivers to be attentive when L2 systems are engaged and prepared to take control of the vehicle at any time (Tesla, n.d.). Tesla monitors driver attention by requiring their hands to be on the steering wheel. Software measures the torque applied by hands holding the steering wheel and uses that as a surrogate for driver attention. This non-vision-based system has been problematic, as it has been reported that some users improvise methods to fool the software into thinking hands are on the wheel (Davies, 2018). This suggests that drivers were willing to exhibit HOW even when the software and manufacturer required their hands to be on the wheel.

Limitations

Naturalistic driving studies have experimental design restraints over controlled-environment studies (e.g., test-track). Specifically, this study lacks a true control for comparison of L2 activation status. Including an L0 vehicle (i.e., no vehicle automation available) could provide a useful comparison to both L2 status conditions. In addition, with all drivers having an uneven number of observations, one driver may have accounted for more of an effect than others. However, this was controlled for by including "Driver_ID" as a random effect in each model.

Participants for this study lived in Northern Virginia or the DC metropolitan area. This dense urban locality may not be representative of other driving environments (e.g., rural) and should be addressed in future research. Further, only 12 participants were included in these analyses, and although efforts were made to exclude bias (e.g., including Driver_ID as random effect), a larger sample size should be used in future research to better represent other populations of interest (e.g., age; Antin et al., 2015).

Conclusions and Recommendations

EOR behavior was investigated regarding L2 status and intersection type on uncontrolled-access roadways. Overall, EOR behavior was higher across all metrics when L2 was active. Intersection type had some influence on EOR behavior, trending towards decreased EOR behavior as intersections became more complex (i.e., turning). Finally, drivers' NOG behavior differed between L2 active and not active status such that modulation began only when turning when the system was active. Further, drivers tended to have higher EOR metrics when traveling under 37 mph, higher EOR metrics when on controlled-access roadways, and increased HOW when L2 was active.

Future research should investigate EOR behavior by including an L0 condition as a control group, more diverse localities (e.g., rural), and a larger sample size.

Additional Products

Project page: https://safed.vtti.vt.edu/projects/evaluation-of-eyes-off-road-during-l2-activation-on-uncontrolled-access-roadways/

Dataset link: https://doi.org/10.15787/VTT1/C9NX7E

Education and Workforce Development Products

A brief presentation was presented to VTTI colleagues during a division meeting on 3/8/22 summarizing the results of this study.

Technology Transfer Products

A journal article hasn't been formally submitted but is currently being drafted.

Data Products

A spreadsheet containing variables and data has been created. A separate tab has a definition explaining each variable in the dataset. This document is available on the Virginia Tech Dataverse: https://doi.org/10.15787/VTT1/C9NX7E.

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