BEHAVIORAL ADAPTATION TO PARTIAL AUTOMATION WITH TORQUE-BASED DRIVER MONITORING: GLANCES, HANDS ON WHEEL, AND EMERGENT BEHAVIORS

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ABSTRACT

Recent studies have shown that partial automation affects driver behaviors, including their choices to engage in non-driving-related tasks. Driver monitoring systems may play an important role in helping to shape driver behavior while using partial automation. This study used naturalistic data to examine (i) how partial automation with torque-based monitoring was associated with engagement in non-driving-related tasks, and (ii) the emergence of "check behavior" in the form of brief steering-wheel nudges as a strategy to avoid monitoring alerts.

Sixteen participants drove an instrumented vehicle for one month each. The dataset included 232 trips covering 73 hours of highway driving. The partial automation system had torque-based monitoring that would alert the driver when no steering input was provided for a time threshold. Semi-Markov Models were applied to characterize the dynamics of hands-on-wheel behaviors.

Drivers spent 38% of their manual highway driving time engaged in at least one non-driving-related task compared to 41% in partial automation. The partial automation driving time was associated with a higher tendency to engage with in-vehicle displays and personal devices. Notably, across nearly all nine task categories, drivers looked to the road and mirrors less frequently when using partial automation compared to manual driving, with large differences observed during manual cellphone use and interaction with the steering wheel. Manual cellphone use and engagement with the center stack were associated with increases in the duration of off-road glances, hands-off-wheel, and more frequent check behaviors. Findings highlight drivers' adaptation to partial automation with torque-based monitoring, including the dynamics of hand behaviors, relative to manual driving. The quality of eye glance and hands-on-wheel in response to, and in anticipation of, driver monitoring alerts may be an important factor in determining whether a partial automation system is used consistently with its design intent, considering system performance, safety scenarios, and other factors.

Keywords: Partial automation, SAE Level 2, non-driving-related tasks, driver monitoring systems, driver engagement, behavioral adaptation, check behaviors, naturalistic driving, Semi Markov Models.

INTRODUCTION

Partial driving automation (L2) is increasingly available in vehicles [1, 2]. These features provide sustained longitudinal (i.e., speed and time headway) and lateral (i.e., steering) vehicle control, while the driver retains full responsibility for overall vehicle functionality, including, but not limited to, supervising system performance, object and event detection, and responding appropriately to the specific circumstances to which the driver and vehicle are exposed. Prior research suggests that L2 may introduce role ambiguity when the driver is not provided sufficient information or feedback to reinforce their role in the driving task [3, 4, 5]. When the driver makes decisions and/or takes actions inconsistent with the design intent of the system, it may contribute to elevated risk. An example of this discrepancy is when drivers increase their engagement in non-driving-related tasks (NDRTs), which could be inconsistent with the system's design for the driver to closely monitor system performance and external hazards [6, 7, 8, 9]. Although advancements in vehicle technology have generally shown benefits in reducing crashes [10] and even that the risk for L2 automation is not elevated [11], the potential impact of increased distraction remains, with it being a major contributor to crashes, injuries, and fatalities [12]. This highlights the importance of continued efforts to reduce the frequency and duration of NDRT engagement if it is not already accounted for in an L2 system implementation.

One large-scale naturalistic study of driver behavior found that drivers increased their engagement in NDRTs after activating an L2 system, with this behavior remaining stable and elevated until before the L2 system was deactivated [9]. Compared to manual driving, during L2 use, drivers exhibited higher rates of hands-free driving combined with extended off-road glances. Findings from a meta-analysis confirm that partial automation was associated with increased NDRT engagement and altered visual behavior, even when subjective workload feels lower [13]. The observed behavioral adaptation in the form of higher NDRT engagement, longer off-road glances, and frequent hands-off-wheel driving under L2 use, underscores opportunities for potentially aiding the driver in performing their driving role when it is inconsistent with the design intent of the system [5, 9, 14, 15, 16].

Driver monitoring systems (DMS) are features designed to mitigate the negative effects of decreased driver engagement by intervening when engagement falls below thresholds that align with an L2 system's implementation. Current implementations employ a variety of input modalities, including steering torque and/or capacitive touch sensors for hands-on-wheel (HoW) detection, and camera-based systems to monitor head pose and gaze direction [17, 18, 16]. Often, DMSs use multimodal cues (visual, auditory, and haptic) to support driver attention on a moment-to-moment basis. In situations where the system determines that the driver needs support, the DMS will issue alerts to direct driver attention back to the road [8]. Depending on the system characteristics, the alerts may also instruct the driver to put their hands back on the wheel, steer the vehicle, or look back at the road.

One consequence of supporting the driver's role through a DMS is that drivers may adapt their behavior to align with the DMS thresholds [8]. When these behaviors affect the driver's ability to supervise the system's performance and detect hazards, they may not be aligned with the design intent of the system, indicating that they are low in their quality of engagement. For example, drivers may perform short "check glances" or steering wheel "nudges" to satisfy DMS thresholds while failing to achieve improved situation awareness.

This study examines how drivers adapt to a torque-based monitoring system, focusing on glance allocation, hands-on-wheel behavior, and NDRT engagement during partial automation and manual driving. Naturalistic data were used to help overcome limitations in police-reported crash data, which may include underreporting, driver biases, and difficulty in causal inference [19]; however, naturalistic data also have challenges related to rarity in crash events and incongruence of factors that contribute to near-crashes compared to crashes [20]. The present analysis uses only non-crash highway driving periods and does not make any conclusions about safety outcomes that result from L2 capability—the focus of this study is on how L2 systems may affect driver behavior. We examined (i) how L2 automation with a torque-based DMS shapes driver engagement in NDRTs, and (ii) the emergence of "check behaviors", including brief steering-wheel nudges (hand contacts $\leq$1.5sec). By analyzing behavioral dynamics, this study provides new insights into how DMSs shape engagement and the emergent strategies drivers use to satisfy system prompts.

METHODS

Participants

Sixteen drivers (19% female) with an average age of 38.3 years (SD=10.8 years) were recruited from the greater Boston area of Massachusetts through advertisements. Potential participants were screened according to inclusion criteria that required them to pass background and driving record checks and to have highway driving as part of their regular commute. Drivers were excluded if they had been involved in a police-reported crash or received two or more traffic violation convictions in the past year, or had other risk markers. Participants received a 30-minute static in-vehicle instruction session followed by an hour of on-road training during which they used the L2 driving automation systems.

Data Source and Data Reduction

Data were drawn from the ongoing MIT-AVT naturalistic data collection effort. The participants in the sample drove a model year 2020 Tesla Model 3 for one month each. The vehicle was equipped with Autopilot, an L2 partial automation system with a highly performative lane-centering feature and a torque-based DMS with hands-on-wheel requirements at the time of the study. Data was collected between April 2021 and December 2022. At the time of the study, the Tesla Model 3 vehicles only had torque-based driver monitoring. No crashes were observed in the dataset. The vehicles were instrumented with data acquisition systems [21, 16] that continuously recorded data from: (i) Controller Area Network (CAN) bus to determine vehicle kinematics, driver interaction with the vehicle controllers, and the state of in-vehicle automation systems, (ii) Global Positioning System (GPS) to record location; (iii) four 720px video cameras that captured (30fps) the driver's face, vehicle cabin, instrument cluster, and the view of the forward roadway. Data collection that supported the creation of this study's dataset was approved by the university's IRB (COUHES), and the IRB number was 1602469764.

Trips that contained some highway driving (assessed via GPS coordinates) were manually reviewed to assess the suitability of videos (illumination, focus, etc.) for annotation. Candidate trips considered for inclusion in the dataset were 15 – 90 minutes in length, with 10% or more of trips consisting of driving on a highway. From the pool of candidates, trips were then selected for inclusion in the dataset, prioritizing cases where the driver used the L2 system for 5% or more of the highway driving. The final dataset included 232 trips covering 73 hours of driving on limited-access highways.

Measures

Glance location. Driver glance location was manually annotated frame-by-frame at 30fps. Glances were classified to the following categories: (i) *Road* (glances directed to the windscreen); (ii) *Instrument Cluster* (instrument cluster or steering wheel location); (iii) *Down & Center Stack* (center stack, the in-car multimedia, and the down or lap location); and (iv) *Mirrors* (left, right windows or mirrors, and rearview mirror). When a glance did not fall under the listed categories, it was annotated as Other. See [15] for a detailed description of glance coding.

Steering wheel control level. The driver's steering wheel control level was manually annotated frame-by-frame at 30fps based on the observed driver hand positioning on the steering wheel [15] and included the following hands-on-wheel labels: (i) *Hands-off-wheel* (driving hands-free); (ii) *Hand/s-on-wheel*; and (iv) Not visible. In addition to these control states, brief contacts of 1.5 sec or shorter of hands-on-wheel between two periods of hands-off-wheel were identified and defined as a *Steering wheel nudge* [16, 22].

Non-driving-related tasks (NDRT). NDRTs were manually annotated frame-by-frame at 30fps [14]. Overall, the coding scheme included a total of ten task categories. The task categories were grouped in the following manner: *Manual Cellphone Use*: including holding, reaching for, or manipulating a personal electronic device; *Voice interaction*: including voice commands or talking on a personal electronic device that was not handheld; *Interacting with center stack*: including reading, watching or manipulating the center stack; *Interacting with Steering Wheel*: including any interaction with the buttons on the steering wheel; *Interacting with Objects*: including reaching for or manipulating an object that was not a personal electronic device; *Interacting with passenger*: including talking to a passenger; *Hygiene*: including any hygiene activity that lasted longer than 3 seconds; *Food and Drink*: including any eating or drinking related activity; *Other*: including relatively rare activities that did not fit into any other NDRT categories (e.g., whistling, talking to self, clapping hands); and *No NDRT*: indicating that the driver was not engaged in any NDRT.

Statistical Analyses

Linear Mixed-effects regression models with NDRT category (including No NDRT) and automation level (manual and L2 driving) as independent variables and driver-specific random intercepts were used to assess the: (i) proportion of engagement in each NDRT category; (ii) proportion of road monitoring (glances to the Road and Mirrors locations); and (iii) proportion of Hand-on-Wheel behavior (HoW). Semi-Markov Models were applied to characterize the transition probabilities of HoW (hands-on-wheel/off-wheel/steering-wheel nudges) behaviors across manual and L2 driving, with and without NDRT engagement.

The use of SMM provides the ability to estimate the transition probabilities between states. Hands-on-wheel data were censored around the boundaries of the NDRT engagement segment to avoid artificially introducing check behaviors as a result of the NDRT extraction process. When calibrating the transition probabilities for the SMMs, the algorithm considered both the present state as well as the next state in the chain. Chains with a length of 1 were omitted.

Missing Data

Because of the nature of naturalistic observation data, some video segments could not be coded for specific behaviors. In certain cases, this was due to environmental factors (e.g., camera glare) or driver-related factors (e.g., wearing dark sunglasses), which prevented reliable assessment of eye gaze. Out of all data, 20% had missing glance data, 40% had missing hand activity data, and 2% had missing secondary activity data. Importantly, including these epochs with missing data in the analysis did not change the overall patterns of results.

FINDINGS

Overall, participants drove 4,869 miles on limited access highways that were characterized by relatively frequent use of automation, with 52% (2,543 miles) in L2, 15% (747 miles) with ACC, and 32% (1,579 miles) in manual driving. No crashes were observed in the dataset. Overall, drivers spent 39% of their highway driving time engaged with at least one NDRT. Compared to manual driving, L2 driving was associated with a slightly higher engagement in NDRTs (41% in L2 vs. 38% in manual driving). Figure 1 shows the estimated prevalence of each category of NDRT engagement when driving with and without the L2 system.

As shown in Figure 1, the proportions of time drivers spent interacting with the center stack and steering wheel were 45% and 100% higher relative to when driving in L2 ($p_{\text{Interacting with center stack}}$=0.16, 95% CI[0.12–0.19] and $p_{\text{Interacting with the steering wheel}}$=0.04, 95% CI[0.03–0.06]) compared to manual driving ($p_{\text{Interacting with center stack}}$= 0.11, 95% CI[0.08–0.14], and $p_{\text{Interacting with the steering wheel}}$= 0.02, 95% CI[0.006–0.03], respectively). The proportion of time engaging in manual cellphone use was higher when using L2 ($p_{\text{Manual cellphone use}}$=0.04, 95% CI[0.01–0.06]) compared to when in manual driving ($p_{\text{Manual cellphone use}}$=0.03, 95% CI[0.009–0.06]). Drivers also had a higher proportion of consuming food and drinks when driving with L2 compared to when in manual driving (L2 $p_{\text{Food and Drink}}$=0.08, 95% CI[0.04–0.11], and manual driving $p_{\text{Food and Drink}}$=0.03, 95% CI[0–0.07]). Lastly, drivers had a lower proportion of hygiene-related engagement when driving with L2 (p_{hygiene}=0.04, 95% CI[0–0.09]) compared to when in manual driving (p_{hygiene}=0.07, 95% CI[0.02–0.12]).

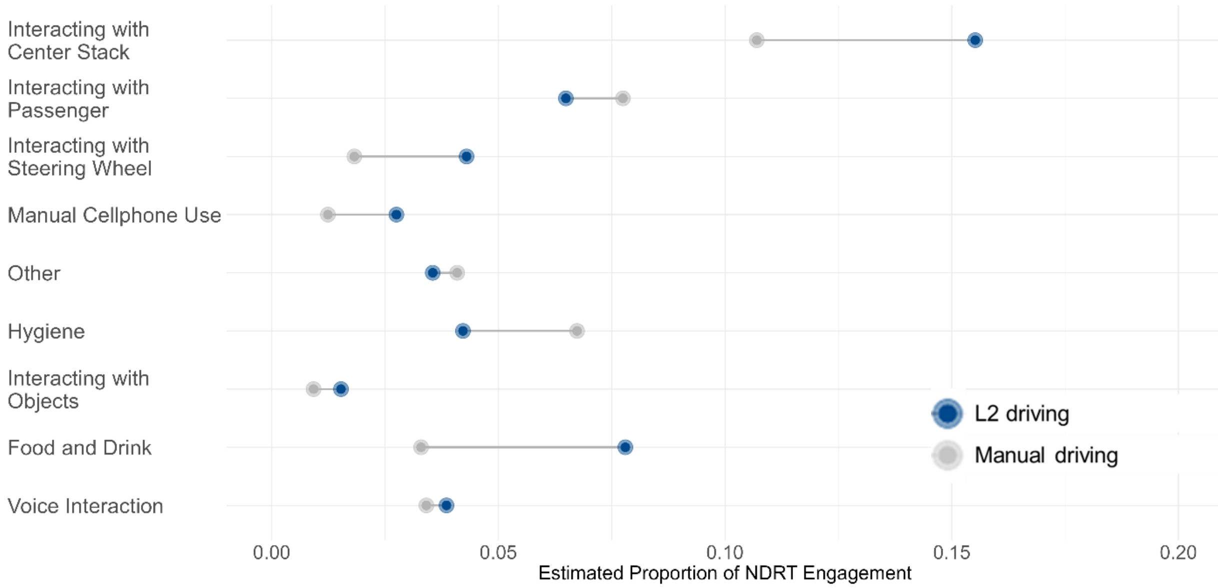

Figure 1. Estimated proportion of engagement in NDRTs in manual driving (gray) and in L2 driving (blue).

Figure 2 illustrates the estimated proportions of the road monitoring, which is defined as the proportion of time drivers looked at the road and mirrors within an NDRT engagement and when just driving (i.e., No NDRT). Overall, the proportion of road monitoring was lower when engaging in NDRTs. Analysis of the proportion of road monitoring across NDRT categories shows that engagement in any NDRT when driving with L2 was associated with a significant decrease in the proportion of road monitoring compared to when in manual driving (see Figure 2). The proportion of road monitoring when driving with No NDRT was relatively high for both manual driving and when driving with L2 (95% and 92%, respectively). Manual cellphone use, interacting with objects in the vehicle, interacting with the center stack, and interacting with the steering wheel categories had the lowest proportion of road monitoring and the largest decrease associated with L2 use compared to No NDRT engagement and to all other NDRT categories. Engaging in manual cell phone use when driving in L2 was associated with a 23% relative decrease in the proportion of road monitoring compared to manual cell phone use in manual driving (L2 $p_{\text{Manual cell phone use}}$=0.33, 95% CI[0.24–0.42], and manual driving $p_{\text{Manual cell phone use}}$=0.43, 95% CI[0.34–0.52]). Interacting with objects in the vehicle when driving in L2 was associated with a 18% relative decrease in the proportion of road monitoring compared to when engaging in this task in manual driving (L2 $p_{\text{Interacting with objects}}$=0.64, 95% CI[0.57–0.72], and manual driving: $p_{\text{Interacting with objects}}$=0.78, 95% CI[0.70–0.87]). Interacting with the center stack, and interacting with the steering wheel NDRT categories when driving in L2 were associated with 7% and 20% relative decrease in the proportion of road monitoring compared to when engaging in these task in manual driving (L2 $p_{\text{Interacting with the center stack}}$=0.52, 95% CI[0.48–0.55], and manual driving $p_{\text{Interacting with the center stack}}$=0.56, 95% CI[0.52–0.60]) and (L2 $p_{\text{Interacting with the steering wheel}}$=0.65, 95% CI[0.60–0.70], and manual driving $p_{\text{Interacting with the steering wheel}}$=0.81, 95% CI[0.75–0.87]), respectively.

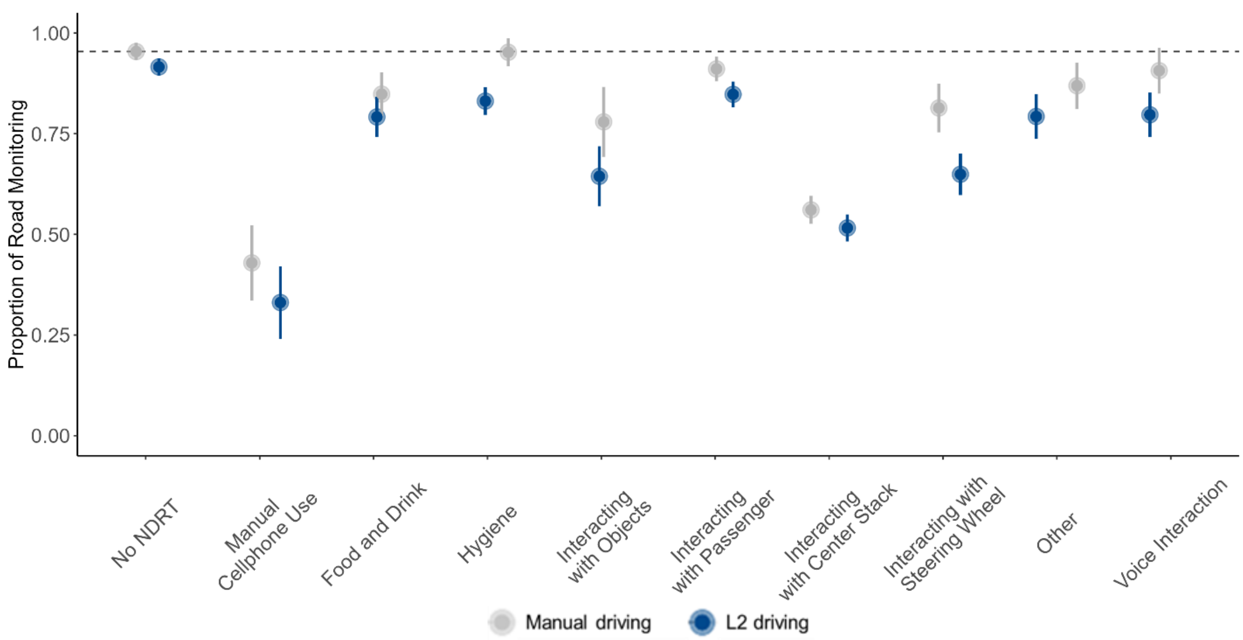

Figure 2. Estimated proportions and 95% CI of road monitoring (glances to the road and mirrors) across NDRT categories, shown for manual driving (gray) and L2 driving (blue). Each NDRT category was modeled separately. The dashed line represents the estimated proportion of road monitoring in manual driving and without any NDRT engagement.

Figure 3 illustrates the estimated proportions of hands-on-wheel (HoW), defined as the proportion of time drivers had at least one hand on the steering wheel within an NDRT engagement and when just driving. Linear mixed-effects models with subject-specific random intercept were used to estimate the proportions of HoW when in manual driving and when using the L2 system, which has a torque-based DMS that requires drivers to maintain hands-on-wheel when engaged. In general, manual driving was associated with the highest proportions of HoW, with drivers keeping their hands on the wheel about 95% of the time (i.e., 5% of hands-free driving) across most NDRT categories. Exceptions include interacting with objects in the vehicle, where drivers were driving hands-free 25% of the time, and food and drink NDRT, which was associated with 16% of hands-free driving, all when in manual driving. Evaluating the proportion of HoW by NDRT category showed that there was a group of NDRT categories with a stronger decrease in the proportion of HoW associated with L2 use. L2 driving without engaging in an NDRT was associated with 10% relative decrease in the proportion of HoW (L2 $p_{\text{No NDRT}}$=0.89, 95% CI[0.83–0.94] vs. manual driving $p_{\text{No NDRT}}$=0.98, 95% CI[0.92–1.00]). L2 driving with NDRTs was generally associated with greater reductions in the proportion of HoW. Exceptions included interacting with the steering wheel, which inherently requires hands-on-wheel, and food and drink, and interacting with objects in the vehicle, both of which already exhibited relatively low HoW proportions during manual driving and showed no differences in proportions of HoW between L2 and manual driving. Manual cell phone use when driving in L2 was associated with a 32% relative decrease in the proportion of HoW compared to Manual cell phone use in manual driving (L2 $p_{\text{Manual cell phone use}}$=0.65, 95% CI[0.55–0.75] vs. manual driving $p_{\text{Manual cell phone use}}$=0.95, 95% CI[0.84–1.00]). Drivers also took both hands off the wheel for a higher proportion of time when engaging in hygiene-related NDRTs in L2 compared to manual driving (L2 p_{Hygiene}=0.68, 95% CI[0.57–0.78] vs. manual driving p_{Hygiene}=0.95, 95% CI[0.84–1.00]).

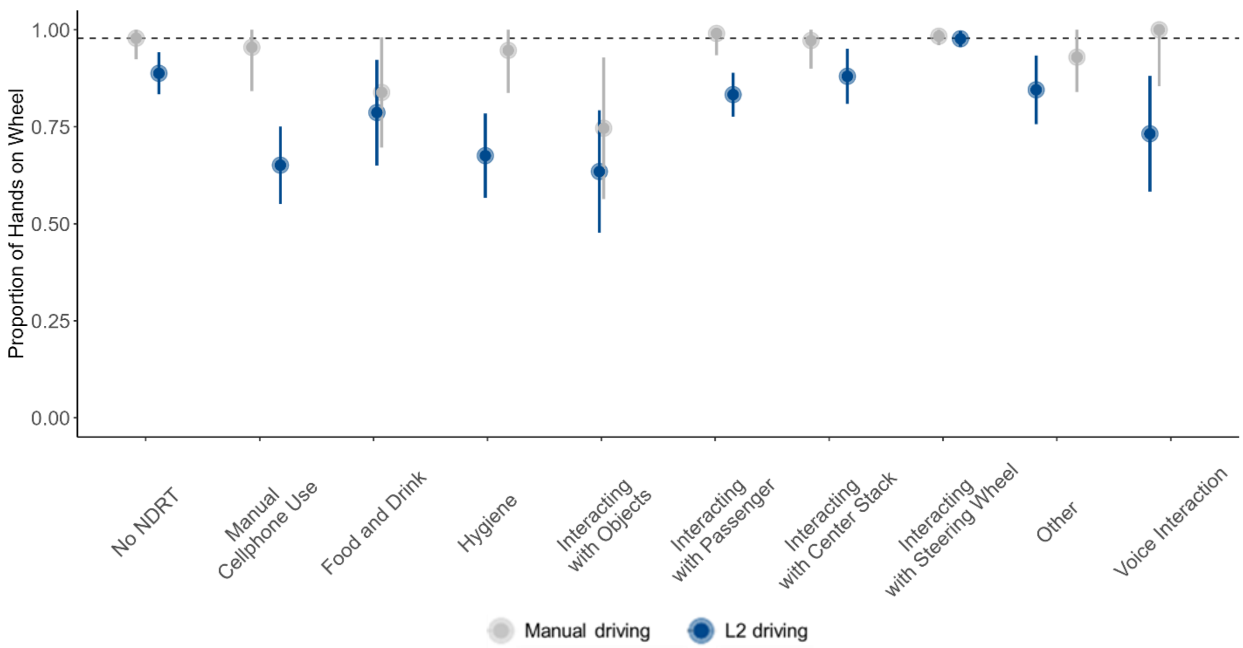

Figure 3. Estimated proportions and 95% CI of proportion of HoW (one or two hands on the steering wheel) across NDRT categories, shown for manual driving (gray) and L2 driving (blue). Each NDRT category was modeled separately. The dashed line represents the estimated proportion of HoW in manual driving and without any NDRT engagement.

Semi-Markov Models (SMMs) were fit to examine how the use of L2 systems with and without NDRT engagement changed the dynamics and patterns of driver vehicle control, including the emergence of "check behavior", and how this behavior was distributed over time. The SMMs for hand behavior include three states: (i) *hands-on-wheel*, (ii) *hands-off-wheel*, and (iii) *steering wheel nudge.* For the current analysis, we generated SMMs for driving manually or with the assistance of the L2 system and included only NDRT categories that were most prevalent and demonstrated relatively high sensitivity to the use of automation in the analysis above. The selected categories include manual cell phone use, interacting with the center stack, interacting with steering wheel, and the No NDRT category as a reference.

The comet plot in Figure 4 compares transition probabilities from hands-off wheel to a steering wheel nudge between manual and L2 driving, for each of the evaluated NDRT categories. Each comet runs from the manual estimate (at the tail) to the L2 estimate (the hollow circle). The length of the comet shows how much the estimates for manual and L2 driving differ for that NDRT category. Longer comets mean bigger differences; shorter comets mean the estimates were more similar. Figure 4 shows the emergence (higher probability) of steering wheel nudges check behavior when using L2 across the several of the evaluated NDRTs. Driving with L2 and without engagement in any NDRT (i.e., No NDRT) was associated with a 170% relative increase in the probability of steering wheel nudges, compared to when driving manually (Figure 4). Using the center stack in L2 driving, drivers had a higher probability for steering wheel nudges compared to when in manual driving ($p_{(\text{Center stack->steering wheel nudge})}= 0.35$ vs. $p_{(\text{Center stack ->steering wheel nudge})}=0.16$, respectively). Lastly, limited differences were observed for interaction with the steering wheel when driving with L2 compared to when in manual driving.

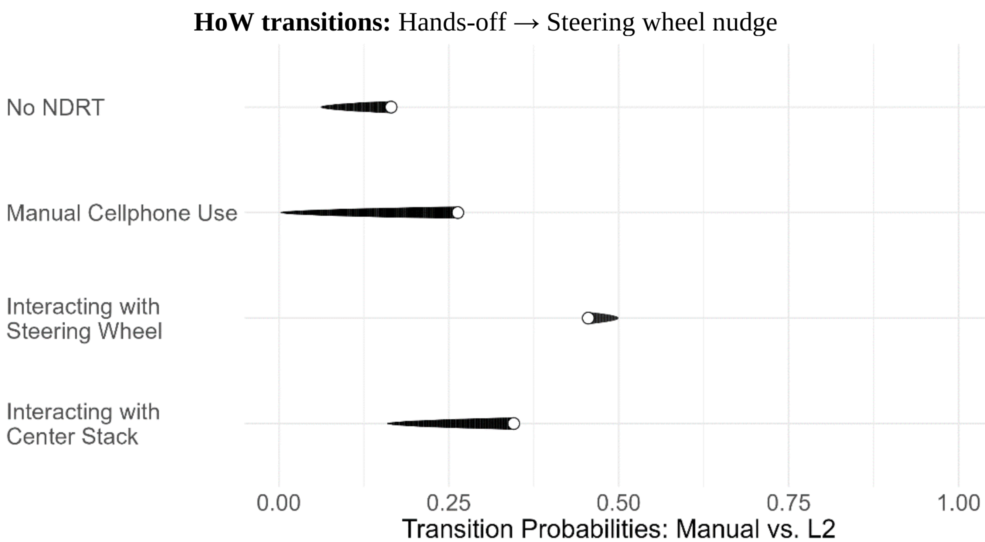

Figure 4. Differences in HoW transition probabilities between manual and L2 driving for different NDRT categories. The comet tail represents the value for manual driving, and the comet head (hollow circle) represents the transition probability when using L2.

DISCUSSION

This study showed that drivers adapt their behavior when using L2 automation with a torque-based DMS, focusing on the prevalence of NDRT engagement and associated check behaviors. By analyzing the dynamics of hands-on-wheel across manual and L2 driving, the study demonstrates how specific partial automation implementations may contribute to the emergence of check behavior, especially when engaging in NDRTs. Consistent with prior research, our findings indicate that drivers devoted a substantial portion of their highway driving time to NDRTs, averaging nearly 40% [9]. Results also showed that NDRT engagement was slightly more frequent (3%) during L2 driving compared to manual driving, with drivers especially more likely to engage in NDRTs that involve in-vehicle displays and personal devices. Drivers spent a higher proportion of time interacting with the center stack and steering wheel controllers, as well as eating or drinking and interacting with their mobile devices during periods of L2 driving. Taken together, these results suggest that partial automation plays a role in reshaping the distribution of tasks performed by the driver compared to manual driving.

In addition to the higher prevalence of engagement in some specific types of NDRTs, our findings show that L2 use was associated with reduced levels of road monitoring and higher proportions of hands-free driving. Across nearly all NDRT categories, drivers looked to the road and mirrors less frequently when using L2 compared to manual driving, with the largest decreases observed during manual cellphone use, interaction with objects in the vehicle, and steering wheel engagement. Similarly, drivers maintained their hands on the wheel less often when driving with L2, even though the system required torque input. Hands-free driving increased substantially during NDRTs such as manual cellphone use and hygiene activities, in some cases reducing hands-on-wheel proportions by more than 30%. Interestingly, many of these same tasks were typically performed in manual driving while maintaining at least one hand on the steering wheel. With L2 automation, however, drivers choose to perform the same tasks with both hands off the wheel. In this sense, L2 use was not only associated with an increase in the prevalence of some NDRT engagement but also changed the way drivers perform these tasks.

Relative to manual driving, our study demonstrated the changes in driver behavior and the emergence of check behaviors when using partial automation with a torque-based monitoring system. Check behavior capture short steering nudges. The elevated prevalence of visually demanding NDRTs was associated with an increased duration of eyes-off-road and hands-free driving, as well as frequent steering wheel nudges. This, in part, may aim to satisfy system requirements and reveal how drivers adapt to monitoring in ways that satisfy system requirements, yet may limit effective state inference.

LIMITATIONS & FUTURE DIRECTIONS

Limitations to the current study include a relatively small, regional, volunteer sample of drivers who were enrolled for one month. Future research should evaluate whether and the extent to which the use of other implementations of partial automation with a torque-based DMS, camera-based, or multimodal systems elicits different adaptations. It is also important to understand if the observations made with respect to L2 driver behaviors correspond only to L2 usage or if adaptive cruise control shares similarities in driver behaviors. As such, future research may assess if some of these behavior changes emerge when adaptive or conventional cruise control are used. Lastly, future research could benefit from longer periods of study to better estimate the longer-term use of automation.

CONCLUSIONS

In this study, we demonstrated how drivers adapted their NDRT engagement when L2 driving automation was used. Notably, drivers showed a slight overall increase in NDRT engagement with changes to the distribution of tasks being performed and the associated behaviors. We also demonstrated the emergence of check behavior that may be attributable to the DMS alerting strategy and may be indicative of less driving information being obtained by the driver. If this behavior affects a driver's ability to supervise system performance or detect hazards, it may be indicative of a lower quality response. The findings may indicate that drivers not only adapt to the L2 system performance but also to its DMS.

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REFERENCES

1. Taxonomy, S. A. E. *Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*–J3016_202104. 2021.
2. Consumer Reports. *Understanding the Current State of Vehicle Automation*. Yonkers, NY: Consumer Reports, 2021. https://data.consumerreports.org/wp-content/uploads/2021/09/CR-Understanding-Vehicle-Automation-Nov-2021-corrected.pdf
3. Bainbridge, Lisanne. "Ironies of automation." In Analysis, design and evaluation of man–machine systems, pp. 129-135. Pergamon, 1983.
4. Victor, Trent, Marco Dozza, Jonas Bärgman, Christian-Nils Boda, Johan Engström, Carol Flannagan, John D. Lee, and Gustav Markkula. *Analysis of naturalistic driving study data: Safer glances, driver inattention, and crash risk*. No. SHRP 2 Report S2-S08A-RW-1. 2015.
5. Morando, Alberto, Pnina Gershon, Bruce Mehler, and Bryan Reimer. "A model for naturalistic glance behavior around Tesla Autopilot disengagements." Accident Analysis & Prevention 161 (2021): 106348.
6. De Winter, Joost CF, Riender Happee, Marieke H. Martens, and Neville A. Stanton. "Effects of adaptive cruise control and highly automated driving on workload and situation awareness: A review of the empirical evidence." Transportation research part F: traffic psychology and behaviour 27 (2014): 196-217.
7. Onnasch, Linda, Christopher D. Wickens, Huiyang Li, and Dietrich Manzey. "Human performance consequences of stages and levels of automation: An integrated meta-analysis." Human factors 56, no. 3 (2014): 476-488.
8. Mueller, Alexandra S., Pnina Gershon, Samantha H. Haus, Jessica B. Cicchino, Bruce Mehler, and Bryan Reimer. "Finding windows of opportunity: How drivers adapt to partial automation safeguards over time." Transportation Research Part F: Traffic Psychology and Behaviour 111 (2025): 112-129.
9. Pipkorn, Linda, T. Zach Noonan, Bruce Mehler, Bryan Reimer, and Pnina Gershon. "Changes in glance and hands-on-wheel behaviors when engaging with non-driving-related tasks while using Tesla Autopilot." Transportation Research Part F: Traffic Psychology and Behaviour 109 (2025): 232-241.

10. Cicchino, Jessica B. "Effectiveness of forward collision warning and autonomous emergency braking systems in reducing front-to-rear crash rates." Accident Analysis & Prevention 99 (2017): 142-152.
11. Aukema, Amy, Kate Berman, Travis Gaydos, Ted Sienknecht, Chou-Lin Chen, Chris Wiacek, Tim Czapp, and Schuyler St Lawrence. "Real-world effectiveness of model year 2015-2020 advanced driver assistance systems." In 27th International Technical Conference on the Enhanced Safety of Vehicles (ESV) National Highway Traffic Safety Administration. Paper, no. 23-0170, pp. 23-0170. 2023.
12. National Highway Traffic Safety Administration. (2021). *Traffic safety facts: Distracted driving 2019* (Report No. DOT HS 813 111). National Highway Traffic Safety Administration.
13. Vasta, Nicola, and Francesco Biondi. "Effect of Partially Automated Driving on Mental Workload, Visual Behavior and Engagement in Nondriving-Related Tasks: A Meta-Analysis." Human Factors (2025): 00187208251323132.
14. Reagan, Ian J., Eric R. Teoh, Jessica B. Cicchino, Pnina Gershon, Bryan Reimer, Bruce Mehler, and Bobbie Seppelt. "Disengagement from driving when using automation during a 4-week field trial." Transportation research part F: traffic psychology and behaviour 82 (2021): 400-411.
15. Morando, Alberto, Pnina Gershon, Bruce Mehler, and Bryan Reimer. "Visual attention and steering wheel control: From engagement to disengagement of Tesla Autopilot." In Proceedings of the Human Factors and Ergonomics Society Annual Meeting, vol. 65, no. 1, pp. 1390-1394. Sage CA: Los Angeles, CA: SAGE Publications, 2021.
16. Gershon, Pnina, Bruce Mehler, and Bryan Reimer. "Driver response and recovery following automation initiated disengagement in real-world hands-free driving." Traffic injury prevention 24, no. 4 (2023): 356-361.
17. Sakai, M., and R. Fuchs. Hands On/Off Detection Based on EPS Sensors.
18. Hynd, D., M. McCarthy, J. Carroll, M. Seidl, M. Edwards, C. Visvikis, M. Tress, N. Reed, and A. Stevens. "Benefit and feasibility of a range of new technologies and unregulated measures in the fields of vehicle occupant safety and protection of vulnerable road users." (2015).
19. Regan, Michael A., Charlene Hallett, and Craig P. Gordon. "Driver distraction and driver inattention: Definition, relationship and taxonomy." Accident Analysis & Prevention 43, no. 5 (2011): 1771-1781.
20. Knipling, Ronald R. "Crash heterogeneity: Implications for naturalistic driving studies and for understanding crash risks." Transportation research record 2663, no. 1 (2017): 117-125.
21. Fridman, Lex, Daniel E. Brown, Michael Glazer, William Angell, Spencer Dodd, Benedikt Jenik, Jack Terwilliger et al. "MIT advanced vehicle technology study: Large-scale naturalistic driving study of driver behavior and interaction with automation." IEEE Access 7 (2019): 102021-102038.
22. Society of Automotive Engineers. "Operational definitions of driving performance measures and statistics." Surface Vehicle Recommended Practice J2944 (2015).