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Driver behavior and the use of automation in real-world driving

Pnina Gershon [a,*], Sean Seaman [b], Bruce Mehler [a], Bryan Reimer [a], Joseph Coughlin [a]

[a] Massachusetts Institute of Technology, Center for Transportation & Logistics, AgeLab. 1 Amherst Street, Cambridge, MA, 02142, USA
[b] Touchstone Evaluations, Inc. 440 Burroughs St, Detroit, MI, 48202, USA

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ABSTRACT

Background: The emergence of partial-automation in consumer vehicles is reshaping the driving task, the driver role, and subsequent driver behavior. When using partial-automation, drivers delegate the operational control of the dynamic driving task to the automation system, while remaining responsible for monitoring, object/event detection, response selection, and execution. Hence, driving has become a collaboration between driver and automation systems that is characterized by dynamic Transfers of Control (TOC).
Objective: This study aimed to assess how drivers leverage automation in real-world driving, identify driver and system-initiated TOCs, and provide a taxonomy to capture the underlying driver behaviors associated with automation disengagement.
Methods: Fourteen participants drove instrumented Cadillac CT6 vehicles for one-month each, yielding 1690 trips (22,108 miles), with a total of 5343 TOCs between manual driving, SAE Level 1 Adaptive Cruise Control (ACC), and SAE Level 2 Super Cruise (SC).
Results: The use of automation on limited access highways was prevalent (40 % of the miles driven were with SC and 10 % with ACC) yet not continuous. Drivers frequently initiated transitions between automation levels (mean = 9.98, SD = 8.32, transitions per trip), temporarily taking over the longitudinal and/or lateral vehicle control. These transitions were not necessarily related to immediate risk mitigation, but rather to the execution of functions beyond the automation system's capabilities or representing preferences in task execution. Driver-initiated TOCs from SC to manual driving followed the structure and temporal aspects of the hierarchical model of driver behavior. *Strategic*, *Maneuver*, and *Control* TOCs were associated with significantly different patterns of vehicle kinematics, automation disengagement modality, and TOC duration. System-initiated automation disengagements from SC to manual driving were rare (1%).
Conclusions: Generalizing from objective, real-world driving data, this study provides an ecologically valid taxonomy for transfer of control building upon the hierarchical model of driver behavior. We show that driver-automation interactions can occur in each level of the hierarchical model and that TOCs are part of the driver's strategic, maneuver, and control levels of decision making. Thus, TOCs are not isolated or rare events, but rather an integral part of an ongoing, continuous and dynamic collaboration. This taxonomy contextualizes TOCs, paving the way for greater understanding of when and why drivers will takeover control, exposes the underlying motivations for TOCs, and characterizes how these are reflected in the driver's actions. The findings can inform the development of driver-centered automation systems as well as policies and guidelines for current and future automation levels.

1. Introduction

The historical role of the driver is undergoing a metamorphosis. The increasing availability of driving automation systems in consumer vehicles is reshaping the driving task, the driver role, and subsequent driver behavior (Noy et al., 2018; Shinar, 2017). Understanding the behavioral ramifications of automation is key for mitigating possible unintended outcomes and achieving the promise automation holds for driving safety and comfort. The Society of Automotive Engineers (SAE) defines a taxonomy of six automation levels, ranging from manual driving (i.e., SAE Level 0 - no automation) to fully self-driving vehicle under all conditions (i.e., SAE Level 5 - full automation) (SAE

* Corresponding author.
E-mail addresses: pgershon@mit.edu (P. Gershon), sseaman@touchstoneevaluations.com (S. Seaman), bmehler@mit.edu (B. Mehler), reimer@mit.edu (B. Reimer), coughlin@mit.edu (J. Coughlin).

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International, 2018). While full self-driving vehicles are not yet available to consumers for purchase, we are now at the stage of partial-automation, where vehicles can simultaneously control the longitudinal (e.g., adaptive cruise control) and lateral (e.g., lane keeping assist) vehicle kinematics on a sustained basis (SAE Level 2) (SAE International, 2018). Still, vehicles with Level 2 automation can, and often do, operate at lower levels of automation (i.e., Level 0 and Level 1). In Level 1, the automation system performs a single aspect of the dynamic driving task, usually referring to Adaptive Cruise Control (ACC) that maintains a set speed and distance from a lead vehicle (SAE International, 2018). When using Level 2 automation, the driver delegates the operational control of the dynamic driving task over to the automation, while remaining responsible for monitoring, object/event detection, response selection, and execution (SAE International, 2018). Hence, with partial-automation, driving has become a collaboration between driver and automation, characterized by dynamic Transfers of Control (TOC) (Gold et al., 2013; Morando et al., 2020; Seppelt and Victor, 2016).

TOCs occur when dynamically transitioning between automation levels based on need, desire, and/or availability. As part of the driving collaboration, both the driver and the automation system can initiate a TOC (Lu et al., 2016; Gershon et al., 2021). Because Level 1 and Level 2 systems are designed to function under specific Operational Design Domains (ODDs), system-initiated TOCs (i.e., takeover requests) occur when the minimal ODD conditions are not met. On the other hand, driver-initiated TOCs may occur in response to or anticipation of either system failure, missing functionality, or at will (Morando et al., 2020; Merat et al., 2014; Louw et al., 2019a). Unique challenges emerge as more and more aspects of the dynamic driving task are automated, and the driver's role pivots towards monitoring, a task in which humans inherently underperform (Hancock, 2017). Prolonged monitoring of the driving automation may place the driver at higher risk for phenomena like driver out-of-the-loop (OOTL), mode confusion, and distracted driving (Norman, 1990; Louw and Merat, 2017; Gaspar and Carney, 2019), all of which may hinder the driver's ability to safely transition back to manual driving (Louw et al., 2019a). Concern over these phenomena, coupled with the known limitations of Level 1 and Level 2 systems, led research to focus on time-critical, system-initiated automation disengagements, and driver-initiated disengagements following "silent failures"—when the system fails, and only the driver can identify the failure and resume manual control (Louw et al., 2019a; Sarter et al., 1997). For example, Louw et al. (2019b) showed that engaging in a visually demanding secondary task during a simulated silent failure of a Level 2 system resulted in lower quality and increased duration of the TOCs. Zeeb et al. (2016) attributed the observed deterioration in TOC quality following silent failures primarily to the cognitive demands of the secondary task and less to the driver's physical readiness to resume control. A growing body of research that focuses on driver-automation interactions and TOCs indicates that extended use of automation may result in slower hazard detection, and longer reaction time to obstacles compared to manual driving (Louw and Merat, 2017; Eriksson and Stanton, 2017a).

Limitations emerge when trying to generalize performance measures from controlled experimental studies that answer the question "What *can* drivers do?" to an ecologically valid understanding of driver behavior, answering the question "What *do* drivers typically do?". This gap can be addressed by naturalistic studies that directly and continuously record real-world driver behavior, capturing the use of automation and TOCs along with comprehensive, moment-to-moment driving data including speed, g-force, lane deviation, engagement in non-driving related activities, passenger presence, and other environmental conditions (Dingus et al., 2006; Fitch et al., 2013; Gershon et al., 2017, 2018a; Gershon et al., 2018b, 2019; Guo, 2019). Although sparse, research on real-world Level 1 and Level 2 production systems suggests that many TOCs are in-fact not system-initiated or responses to surprise events (Morando et al., 2020; Gershon et al., 2021). Endsley (2017), in a single-subject naturalistic study, observed that Autopilot (Tesla's Level 2 system) appeared to require frequent complex decisions regarding automation engagement and disengagement — suggesting that other forms of TOCs besides system-initiated disengagements or time-critical driver interventions are pertinent to driving safety research.

To understand the use of driving automation and the potential impact various factors have on driver-automation interaction, there is a need to incorporate TOC behavior into a broad and structured framework. For this purpose, we used the hierarchical model of driver behavior (Michon, 1985), which is designed to explain and predict complex, real on-road behaviors. The model breaks down driver behavior into three levels: strategic (planning), maneuver (tactical), and control (operational). The strategic level involves trip-level planning activities, such as identification of trip goal, route, and time constraints. This type of behavior is planned, proactive, and may become apparent over a time course longer than a few seconds (e.g., over minutes or even longer periods). The maneuver level of driver behavior involves tactical control of the vehicle, determined by both the driver's strategic goals (intrinsic) and current driving situation (exogenic). This behavior is typically executed across an interval of seconds. The finest scale of driver behavior is the control level, which is reactive, immediate, and often involves automatic action patterns that are executed at the millisecond time scale (Michon, 1985; Ranney, 1994).

Driver-automation interactions can occur in each level of the hierarchical model of driver behavior. Hence, TOCs are part of the driver's strategic, maneuver, and control levels of decision making. As such, TOCs at each level will have different characteristics including kinematics, mode of interaction, and temporal patterns. TOCs at the strategic level represent proactive and deliberate decisions to disengage automation as part of a plan that may consider aspects like location, time availability, and comfort. TOCs at the maneuver level involve negotiation of a driving scenario such as gap acceptance when overtaking a lead vehicle. In maneuver TOCs drivers elect to disengage automation in response to environmental inputs and the plan requirements. Finally, TOCs at the control level are tied to an immediate, often reflexive reaction patterns in response to environmental cues and feedback from higher levels of the model. We postulate that while simulation studies, by definition and by design, are mostly restricted to address operational TOC behavior, the use of naturalistic methods captures all three levels of driver behavior, allowing the study of strategic, tactical, and operational TOCs.

This study provides a taxonomy that defines TOCs based on the hierarchical model of driver behavior, and by that incorporates driver-automation interactions into a larger, well established, and ecologically valid framework of driver behavior. This approach thus considers TOCs not in isolation or as rare events, but rather as an integral part of an ongoing, continuous and dynamic collaboration. Using real-world, naturalistic driving data, we assessed how drivers leverage different automation levels, characterized the transitions between levels, identified who initiated the transition, and the underlying driver behavior patterns associated with complete automation disengagement.

2. Methods

2.1. Participants

A total of fourteen drivers (36 % female) with an average age of 42 years old (SD = 13.3 years old) participated in the study. Drivers from the greater Boston area of Massachusetts were recruited through flyers and online advertisements. Potential participants were screened according to inclusion criteria that required participants 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 (e.g., selected criminal records, or previous license suspension). Participants were provided with an MIT-owned vehicle for one month along with paid tolls and a monetary incentive of $50 to complete a post drive interview. Prior to vehicle delivery, participants received training on the available automation including Level 1 (ACC) and Level 2 (SC) systems. The training session started with a 30-minute static in-vehicle instruction period followed by an hour of on-road training. During the training drive, participants were familiarized with and were asked to interact with the different automation systems.

2.2. Data collection

The dataset was drawn from the ongoing MIT Advanced Vehicle Technology (MIT-AVT) naturalistic data collection effort (Fridman et al., 2019). As part of the study, participants drove MIT's instrumented 2018 Cadillac CT6 vehicles for a period of one month each (between April 2018 and May 2019). The study vehicles were instrumented with RIDER (Real-time Intelligent Driving Environment Recording) data acquisition system (Fridman et al., 2019) that continuously collected 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 mileage and location; (iii) four 720p video cameras that continuously captured (30 fps) the driver's face, vehicle cabin, instrument cluster, and the view of the forward roadway. Together, these multiple data sources and data types provided rich and comprehensive data related to the vehicle state, driving environment, driver behavior, and the use of automation. At the time of writing, Cadillac CT6′s Super Cruise (hereafter SC) is one of the most advanced, commercially available SAE Level 2 automation driving systems (Monticello, 2020), capable of simultaneously performing the longitudinal and lateral aspects of the dynamic driving task on a sustained basis. When engaged, SC enables hands-free driving while continuously monitoring the driver's head orientation to the forward roadway (as a proxy measure for visual attention) using a driver facing camera. SC is geofenced and only available for use in mapped, limited access highways.

2.3. Data reduction

The TOC dataset included a total of 5343 transitions in automation level between manual driving, ACC, and SC that were identified across 1690 trips (22,108 miles). The transitions in automation were flagged based on data coming from the CAN bus, and then were manually annotated by trained coders following a rigid annotation protocol. Coders further annotated who initiated the transition (driver or system), and the engagement/disengagement methods for driver-initiated transitions (button press, steering, or braking). GPS and video data were used to extract road type and driving conditions. TOCs from SC to manual-driving, that capture complete automation disengagement (driver and system -initiated, n = 428), were further annotated (double coded and mediated) to classify the TOC type as Strategic, Maneuver, or Control, based on Michon's (Michon, 1985) hierarchy of driver behavior, or as system-initiated TOC.

2.4. Measures

For each TOC event from SAE Level 2 (SC) to SAE Level 0 (manual driving), we derived the following qualitative and quantitative measures:

TOC type. TOCs were classified as one of four possible types: (i) *Strategic* TOC, characterized by proactive behavior that occurs on a relatively long-time scale (order of minutes), with supporting evidence that the transition is part of the driver's plan, such as repetition across trips. For example, TOCs occurring proximal to, or immediately after a navigation cue to exit the highway (GPS and/or road signs), switching lanes to the exit ramp, all of which were followed by exiting the ODD. (ii) *Maneuver* TOC, incorporates elements of the plan (i.e., proactive) together with environmental inputs (i.e., reactive), and is part of managing the driving task at the tactical level. This behavior is typically characterized by relatively complex, observable action patterns, that are executed at the time-scale of seconds. For example, elective behavior of passing a lead vehicle in order to maintain current speed, i.e., a combination of plan and environment. (iii) *Control* TOC, characterized by fast and automatic reaction to an identifiable environmental input. This TOC is completely embedded in the operational aspects of driving, and involves automatic action patterns that are executed at the millisecond level. For example, responding to sudden braking of a lead vehicle (iv) *System* initiated TOC, characterized by a takeover request issued by the system, prior to any driver action that can initiate a TOC as specified above (i.e., button press and brake). TOC type was coded independently by two experienced, human annotators (i.e., double-coded) with high inter-rater reliability (*Cohen's kappa* = 0.88, $p < .001$) (Sim and Wright, 2005). Disagreements between the two annotators were mediated.

TOC duration. Defined as the time gap in seconds between the TOC onset and the subsequent change in automation level (e.g., from SC to manual driving) as captured by the CAN bus.

TOC kinematics. Defined as the speed (mph) and g-force (m/s^2) averaged across the TOC duration.

TOC modality. Defined as the mode used to disengage SC, including button press, brake, and takeover request initiated by the automation system. TOCs initiated by a button press or a takeover request were manually annotated from video, while TOCs initiated by braking were captured from CAN bus data and then further annotated. Annotation of TOC modality was double coded with high inter-rater reliability (*Cohen's kappa* = 0.91, $p < .001$; note, that the estimated inter-rater reliability might be sensitive to the relatively high tendency to disengage SC using the brake). Disagreements between the two annotators were mediated.

Prevalence of automation re-engagement. Defined as the proportion of TOCs from SC to manual driving that were followed by automation re-engagement within the same trip.

2.5. Statistical analysis

Linear Mixed-Effects models were used to evaluate the associations between automation level (i.e., Level 0, Level 1, and Level 2) and two outcome variables – miles driven and driving duration. Each model included a driver-specific random intercept to capture between-driver variability. Generalized Linear Mixed-Effects models with driver-specific random intercept (Gamma family) were used to evaluate associations between TOC type (i.e., Strategic, Maneuver, or Control TOC) and the following dependent variables: TOC duration, vehicle speed, and g-force. Lastly, a Mixed-Effects logistic regression model with driver-specific random effects was used to estimate the likelihood of braking or pressing a button as the mode of automation disengagement for the different TOC types. Statistical significance was defined at the level of 0.05 with 95 % confidence intervals.

3. Results

3.1. Characteristics of automation use in the wild

During the data collection period, participants drove 22,108 miles, with 67 % (14,702 miles) in manual-driving, 9% (1891 miles) with ACC engaged (i.e., SAE Level 1), and 25 % (5514 miles) with SC engaged (i.e., SAE Level 2). Driving on limited access highways accounted for 62 % of the recorded mileage, and was characterized by relatively frequent use of automation, mostly SC (40 % of the miles on limited access highways were with SC, and only 10 % were with ACC alone). While the use of automation was prevalent, it was not continuous, from initial engagement to when exiting of the ODD. Drivers often took control over either the longitudinal, lateral, or both vehicle functionalities, dynamically transitioning between automation levels (mean = 9.98, SD = 8.32, transitions per trip). Additionally, on limited access highways where both ACC and SC were available, drivers tended to use SC for longer distances (mean = 3.0 miles, SD = 4.86, $p < .001$) and durations (mean=2.79 min, SD=4.40, $p < .001$) compared to ACC. ACC was used primarily as a temporary state, when drivers overrode SC by either steering or accelerating (mean = 0.74 miles, SD = 1.71; mean=0.73 min, SD= 1.89 respectively). In addition, despite the broad operational design domain (ODD) of ACC, it was rarely used under non-highway conditions (only 7% of the off-highway miles). Fig. 1 summarizes the proportions of driver and system -initiated transitions between automation levels, across all trips and miles driven. When disengaging SC, drivers were more likely to transition to ACC (73 %) than to manual driving (27 %). Driver-initiated transitions from SC to ACC (59 %) were mostly related to a missing functionality of SC (e.g., the ability to change lanes), and the system-initiated transitions (14 %) were mainly in response to leaving the ODD. Complete automation disengagements, from SC to manual driving, were primarily driver-initiated (23 %) vs. system-initiated (1%) where SC issued an immediate takeover request due to either an inattentive driver or exiting the ODD. For 3% of the transitions from SC to manual driving, it was not possible to determine who initiated the transition.

Fig. 1 depicts the dynamic nature of automation use and how drivers transition between automation levels. Among all of these transitions, complete automation disengagements from SAE Level 2 to manual driving, which has been the focus of both industry and academic research as this type of driver takeover is often perceived as the outcome of an immediate need to mitigate possible risk, represented only about a quarter of the observed transitions from Level 2. In order to better understand a driver's decision to completely disengage automation, we first need to characterize the driver's behavior in terms of goals, intentions, and limitations in the context of the driving task. We build on the hierarchical model of driver behavior (Michon, 1985) as a framework to study automation disengagement, assessing why drivers disengage automation and takeover control of the dynamic driving task, and providing a methodological approach for determining whether these automation disengagements are primarily a reactive response or an execution of a planned behavior.

3.2. Evaluating the characteristics of driver behavior in automation disengagement

In total, 399 TOCs from SC (i.e., SAE Level 2) to manual-driving (i.e., SAE Level 0) were categorized into one of three possible types of driver-initiated TOCs, Strategic (31.6 %), Maneuver (11.8 %), Control (56.4 %), or as Accidental (0.02 %) TOC. The distribution of TOC types across the different levels of the hierarchical model demonstrates that complete automation disengagements, from SAE Level 2 to SAE Level 0, are not necessarily related to a single reflexive, moment-to-moment behavior that is associated with the lowest level of the driving task (i.e., Control), but can also be part of a planned behavior (i.e., Maneuver or Strategic). Table 1 summarizes the average TOC duration, speed, and g-force during a TOC by TOC type.

To examine the similarities and differences between the TOCs types in more depth, probability density functions were derived for the three measures. Fig. 2a illustrates the kernel density estimates of TOC duration across TOC types (in gray), as well as modeled mean estimates and the corresponding 95 % CIs (in red). TOC duration represents the time interval between a brake-reaction or button-press and the complete takeover by the driver. Accordingly, as SC allows hands-off-wheel driving, the TOC duration from onset is dictated by the time it takes the driver to resume steering control (i.e., active steering). Overall, the distribution of Control TOC duration was characterized by a heavy-tail, compared to the distributions of the Strategic and Maneuver TOCs. The results show a significant association between TOC duration and type. The estimated duration of Control TOCs was significantly longer (0.87 s, 95 % CI: [0.72, 1.06]) than the estimated durations of Maneuver (0.55 s, 95 % CI: [0.43, 0.71], $p < .001$) and Strategic (0.58 s, 95 % CI: [0.48,0.71], $p < .001$) TOCs. In proactive TOCs (i.e., Strategic and Maneuver), drivers were more likely to have their hands on the wheel prior to initiating the disengagement, while in reactive TOCs (i.e., Control) drivers were more likely to reach towards the steering wheel only after initiating the disengagement.

Table 1
Mean and standard deviation (SD) of TOC duration, vehicle speed, and g-force by TOC type.

	TOC duration (sec) mean (SD)	TOC speed (mph) mean (SD)	TOC g-force (m/s^2) mean (SD)
Strategic TOC	0.63 (0.45)	69.04 (8.78)	−0.03 (0.05)
Maneuver TOC	0.61 (0.43)	52.79 (27.23)	−0.04 (0.08)
Control TOC	0.96 (0.63)	45.46 (24.77)	−0.12 (0.13)

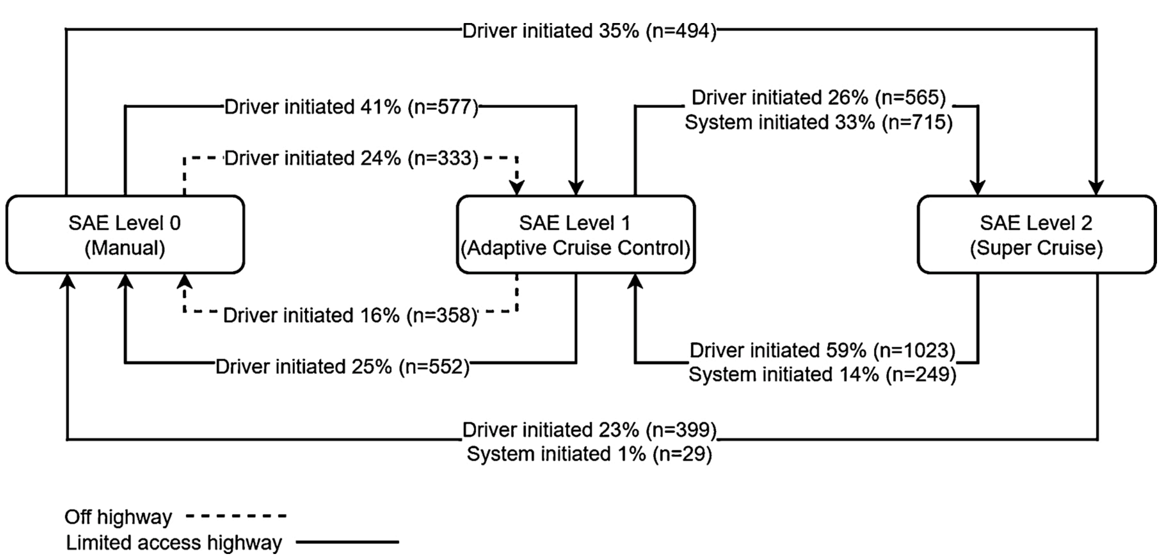

Fig. 1. Proportion of TOCs between automation levels across all the trips in the dataset. The arrows indicate the direction of transition and the proportion of transitions from one level to the other, such that arrows coming out of an automation level sum to 100 %. Note: For 3% (n = 49) of the TOCs from SC to manual driving the information of who initiated the transition was not available.

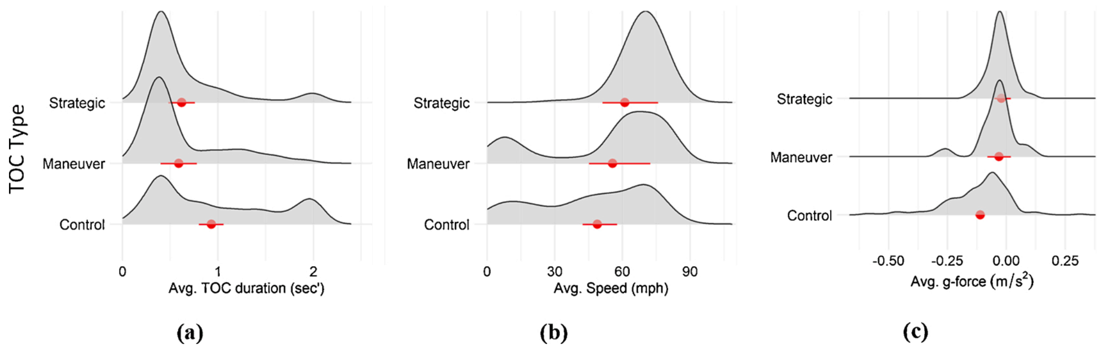

Fig. 2. Density function of (a) average TOC duration, (b) the average speed and (c) the average g-force during the TOC. In red, model estimates with 95 % confidence intervals (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Vehicle kinematics, expressed as the average speed and g-force during a TOC, were also sensitive to the TOC type (Figs. 2b and c, respectively). The estimated average speed during a Control TOC was substantially lower (48.85 mph, 95 % CI: [42.35, 57.70]) than the average speed of Strategic TOC (61.09 mph, 95 % CI: [51.18, 75.78], $p <$ .001). The average speed of Maneuver TOCs did not differ significantly from either the average speed of Control or Strategic TOCs. While the density distribution of Strategic TOCs followed a clear unimodal shape, the average speed of the Control TOCs was more uniformly distributed. The observed bimodal distribution of the Maneuver TOCs may indicate that two classes of maneuvers underlie these TOCs, likely representing free flow vs. stop-and-go driving maneuvers (see Fig. 2b).

Control TOCs were characterized by significantly stronger deceleration (see Fig. 2c), indicating a stronger braking reaction (-0.11, 95 % CI: [-0.13, -0.09]) compared with Maneuver (-0.03, 95 % CI: [-0.08, 0.02], $p <$ .001) and Strategic (-0.02, 95 % CI: [-0.05, 0.02], $p <$ .001) TOCs. While the average g-force in Strategic and Maneuver TOCs showed a relatively narrow distribution around zero, the g-force values of Control TOCs were more widely distributed, with frequent and stronger negative values. In fact, elevated driving kinematic events (g-force $\leq$ -0.4m/s2) (Gershon et al., 2018a; Simons-Morton et al., 2019) were observed only in Control TOCs (4%). The average g-force did not differ between Maneuver and Strategic TOCs.

As mentioned earlier, drivers could disengage automation by braking or pressing a button located on the steering wheel. A Mixed-Effects logistic regression model with driver-specific random effects that captured between-participant variability was used to evaluate the associations between TOC type and the mode of automation disengagement. While the overall probability to disengage SC by braking was higher than the probability of pressing a button, the probability of braking as the mode of disengagement was significantly higher in Control TOCs (0.97, 95 % CI: [0.92, 0.99]) than in Maneuver (0.69, 95 % CI: [0.40, 0.88], $p <$ .001) and Strategic (0.63, 95 % CI: [0.37, 0.82], $p <$ .001) TOCs.

Lastly, we examined whether different sequential dependencies emerged based on the TOC type. Fig. 3 illustrates the tendency of drivers to re-engage in any level of automation within a trip, following each type of driver-initiated Level 2 to manual driving disengagement. The sequential behavior within a trip indicated that drivers were most likely to reengage automation following Control and Maneuver TOCs (83 % and 81 %, respectively). In contrast, following Strategic TOCs, drivers were more likely to maintain manual driving for the rest of the trip (69 %) and did not re-engage automation very often (31 %).

4. Discussion and conclusions

The surge in vehicle automation technologies and the emergence of partial-automation in consumer vehicles call for an objective investigation of the subsequent changes in driver behavior. This study provides novel insights into driver behavior and the use of automation in real-world, naturalistic driving. Utilizing a total of 14 months of driving data that capture more than 22,000 miles driven in instrumented vehicles, we assessed how drivers leveraged different automation levels, characterized the transitions between levels, identified who initiated the transition, and assessed the underlying driver behavior patterns associated with complete automation disengagement.

Our findings indicate that, when available, most drivers prefer to use higher levels of automation, i.e., relinquishing control of both the longitudinal and lateral aspects of the dynamic driving task over to the automation system, and adapting a monitoring-oriented role. While the use of Level 2 automation was prevalent, it was not generally continuous from initial engagement through to when exiting the ODD. Drivers dynamically transitioned between automation levels, temporarily taking control over either the longitudinal, lateral, or both functionalities of the driving task. These transitions were not necessarily related to mitigation

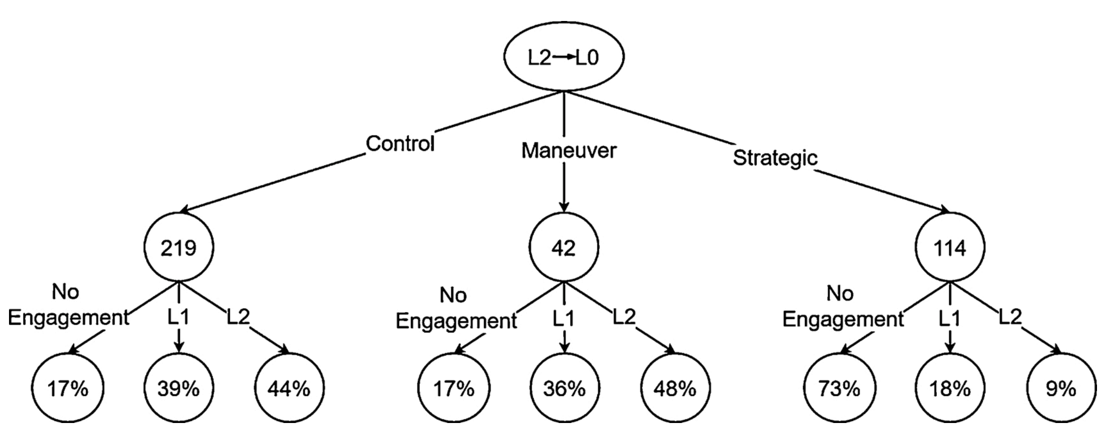

Fig. 3. Sequential behavior and the proportion of automation re-engagement following a complete TOC.

of an immediate risk, but rather to execute functions that were beyond the current automation capabilities (e.g., passing another vehicle), or represent driver's preferences in function execution. Overall, at the trip level when driving on limited access highways, drivers tended to use Level 1 systems as an intermittent state between longer periods of Level 2 system use. This finding was supported by the frequent, yet relatively short periods/road segments of Level 1 usage. Interestingly, despite its availability, we did not find a similar tendency to use assistive automation systems (Level 1) when driving off-highway.

We utilized the hierarchical model of driver behavior (Michon, 1985) to explain driver-initiated automation disengagement and to facilitate the generalization of the observed driver behaviors beyond the current study. While the hierarchical model is a well-established and widely used driver behavior model, this paper is the first to describe automation disengagement in light of the model's principles. Complete automation disengagements are situations where the driver takes back control of the entire dynamic driving task, resuming manual driving. Our data show that these transitions accounted for 27 % of the total transitions from Level 2, the majority of which were driver-initiated (23 %), 3% were uncodable, and only 1% were system-initiated transitions. Thus, it was in only a very few cases that the system issued a takeover request due to either driver inattention or changes in the driving environment (exiting the ODD). A large body of research, mainly simulation and survey studies, has focused on Level 2 and Level 3 system-initiated TOCs, evaluating the driver's ability to regain control in a timely manner and with adequate quality (Rudin-Brown and Parker, 2004; Shen and Neyens, 2017). The current study objectively quantifies the frequency of system and driver-initiated TOCs in naturalistic driving, predominantly showing that system-initiated TOCs are relatively rare, at least for the automation implementation studied. This highlights the need for extensive data collection to study driver behavior and system-initiated automation disengagement in naturalistic settings.

Our findings indicate that driver-initiated automation disengagement follows the structure and temporal aspects of the hierarchical model of driver behavior. Strategic TOCs, representing planned and regulated driver behavior, are characterized by low variability in the distributions of speed and g-force. Strategic TOCs often occur at relatively high speed, with only subtle fluctuations in speed (i.e., low g-force values). These changes in vehicle kinematics indicate a tendency of drivers to strategically disengage automation, by gently tapping the brake pedal (not necessary to change speed) or pressing the disengagement button. In contrast, the high variability across all measures of Control TOCs highlights the reactive nature of the transitions, and the less predictable conditions under which they occur. Most of the Control TOCs were initiated by a brake pedal press (97 %) and were associated with a stronger deceleration compared to Strategic and Maneuver TOCs. Additionally, the overall longer duration of Control TOCs was likely an outcome of the time it took drivers to grab the wheel and actively steer. As SC (a Level 2 system) allows hands-free driving when engaged, it is likely that in planned behavior (i.e., Strategic and Maneuver) TOCs, the act of placing the hands on the wheel, occurred before the TOC onset, making the takeovers shorter than in reactive TOCs (i.e., Control TOCs).

Out of all the driver-initiated TOCs, the Maneuver TOCs from Level 2 to manual driving were the least represented in our data. In contrast, as SC (Level 2) allows the driver to actively steer without completely disengaging (i.e., overriding), we find many maneuver-related TOCs between Level 2 and Level 1 (see Fig. 1). The Maneuver TOCs from Level 2 to manual driving were characterized by kinematics, duration, and mode of disengagement that are in-between Control and Strategic TOCs, leaning more toward the latter. Lastly, assessing the temporal dependencies between transitions, we find that subsequent to Control and Maneuver TOCs drivers were very likely to re-engage automation, reinforcing that the disengagement was in response to an exogenous catalyst to the driver's plan. In contrast, after Strategic TOCs drivers were most likely to maintain manual driving for the rest of the trip. These findings are in line with several simulation studies that show how urgency, time budget, secondary task engagement, and environmental conditions, among others, are associated with variability in TOC duration and quality (Louw et al., 2019b; Eriksson and Stanton, 2017b; Kircher et al., 2013). As such, using the hierarchal model taxonomy to characterize these TOCs, whether as self-paced (Eriksson and Stanton, 2017b) or tactical maneuvers (Kircher et al., 2013), can provide an integrative view of driver behavior.

Taken together, the prospect of higher automation (SAE Levels 3, 4, and 5) and roads shared by mixed fleet vehicles that dynamically transition between automation levels, calls for extending the hierarchical model to explicitly include the automation level in use. The design of both in-vehicle and external human-machine interfaces (eHMIs) should support TOCs and decisions at each level of the model. Additionally, higher levels of automation may embed human like TOC behaviors that follow the hierarchical model. Concurrently, new policies regarding higher levels of automation should consider how to reconcile automation heterogeneity in mixed fleet vehicles, and use the proposed taxonomy to determine acceptability of TOC types in each automation level (Biever et al., 2020).

There are several limitations to the current study, including a relatively small, regional, volunteer sample, without a history of crashes or recent traffic violations. Additionally, we only followed the drivers for one month of driving. Future research could benefit from longer periods of study to better estimate the longer-term use of automation, document more instances of the rare system-initiated disengagements, evaluate temporal patterns of automation use, and capture learning and behavior changes over time. Future research could also expand the application of the hierarchical behavioral model to other types of TOCs, not limited to complete automation disengagement, and examine associations with different environmental and driver related factors. Finally, we encourage further research and comparisons that examine how the characteristics of different Level 2 systems beyond Cadillac Super-Cruise may influence driver automation disengagement behavior.

In conclusion, we find that while driver acceptance of partial-automation (i.e., Level 2 systems) is relatively high, drivers frequently initiate transitions between automation levels for different motivations and reasons. Generalizing from objective, real-world driving data, this study provides a taxonomy for transfer of control building upon the hierarchical model of driver behavior. This taxonomy contextualizes TOCs, paving the way for greater understanding of when and why drivers will takeover control, exposes the underlying motivations for TOCs, and characterizes how these are reflected in the driver's actions. Describing TOCs, not in isolation and as rare events, but rather as an integral part of continuous and dynamic collaboration between driver and automation will inform the development of driver-centered automation systems, policies, and guidelines for current and future automation levels.

Author statement

Dr. Gershon Conceptualization, Methodology, Formal analysis, Writing-original draft, Writing-reviewing & editing, and Supervision. Drs. Seaman, Reimer, Coughlin and Mr. Mehler assisted with Writing-reviewing & editing. All co-authors approved the final manuscript as submitted.

Declaration of Competing Interest

The authors report no declarations of interest.

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