

Situation Awareness, Scenarios, and Secondary Tasks: Measuring Driver Performance and Safety Margins in Highly Automated Vehicles

Madeleine Gibson, John Lee, Vindhya Venkatraman, Morgan Price, Jeffrey Lewis, Olivia Montgomery, and Bilge Mutlu
University of Wisconsin

Joshua Domeyer and James Foley
Toyota Technical Center USA, Inc.

ABSTRACT

The rapid increase in the sophistication of vehicle automation demands development of evaluation protocols tuned to understanding driver-automation interaction. Driving simulators provide a safe and cost-efficient tool for studying driver-automation interaction, and this paper outlines general considerations for simulator-based evaluation protocols. Several challenges confront automation evaluation, including the limited utility of standard measures of driver performance (e.g., standard deviation of lane position), and the need to quantify underlying mental processes associated with situation awareness and trust. Implicitly or explicitly vehicle automation encourages drivers to disengage from driving and engage in other activities. Thus secondary tasks play an important role in both creating representative situations for automation use and misuse, as well as providing embedded measures of driver engagement. Latent hazards-hazards that exist in the road environment and merit driver attention, but do not materialize to require a driver response-have been used with great success for understanding the vulnerability of novice drivers. Latent hazards might provide a similarly useful index of driver attention to the road during periods where the automation is vulnerable to failure. With highly automated vehicles, latent hazards include potential roadway threats that might not be sensed by the automation and would require driver attention. This paper describes driving simulator scenarios used to operationalize automation-relevant latent hazards, secondary tasks tuned to index driver disengagement from the driving task, and measures that reflect safety margins rather than driving performance, such as drivers' trust, situation awareness, and expected time to transition to manual control.

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INTRODUCTION

Sophisticated technology is already active in vehicle control. Driver assistance systems support lane keeping, parking, speed maintenance, blind spot monitoring, and they also enhance night vision and detect driver impairment. In general, the potential safety benefits of these safety systems and automated vehicles are promising; however, realizing this promise depends on carefully coordinating driver and vehicle behavior. As vehicles become more capable, this coordination can break down if the drivers' role is not clear.

Types and Levels of Automation

The types and levels taxonomy of automation [1,2] describes how different sets of activities can be allocated to the automation and to what degree. For each stage of information processing from perception to control, levels of automation can range from none to complete. Taxonomies that guide design of vehicle automation [3,4] share some similarities with the types and levels taxonomy: at one extreme the driver does everything and at the other the automation

takes full control. The National Highway Traffic Safety Administration (NHTSA) and the Society of Automotive Engineers (SAE) define Level 1 vehicle automation as those that perform one primary vehicle control function - either steering or speed maintenance, while the driver performs the others, monitors the roadway, and remains fully responsible for safe vehicle control. Such automation is available in many vehicles today, for example, where the driver steers manually and engages cruise control. In NHTSA and SAE Level 2 automation, the automation performs at least two primary controls, for example both steering and speed maintenance. The driver is responsible for monitoring the roadway and should be ready to take-over control of the vehicle at any time [3]. Level 3 automation, from both NHTSA and SAE definitions, assigns higher capability to the automation, where the vehicle automation monitors the roadway and performs the primary control tasks; however, the driver may be expected to occasionally take control of the vehicle when the roadway demands exceed the capacity of the automation. The crucial concern for Levels 2 and 3 automation is the potential driver confusion regarding when the driver or the automation is

primarily responsible for driving. NHTSA Level 4 and SAE Level 4 and Level 5 represent automation that can handle all driving situations and requires very limited control input from the driver.

Both Level 2 and Level 3 automation require some amount of driver attention to the roadway, either continuously, at critical moments, or during transitions between levels of automation. Attention to the road for monitoring, compared to attention for control, leads to longer response times and less effective responses [5, 6, 7]. Perception for control involves visual, cognitive, and proprioceptive engagement that is coupled to drivers control inputs and the expected outcomes. Activating vehicle automation can sever the perception-action loop and transform the driver from a controller to a monitor. As a monitor, a driver is *on* or *out* of the control loop rather than *in* the control loop [8,9]. Being *on* the control loop implies the driver is not perceiving the vehicle and roadway state to control the vehicle, but is actively monitoring the vehicle and roadway state to ensure the automation is controlling effectively. With automation that assumes control of steering and speed, drivers might easily disengage from monitoring and slip from on the loop to out of the loop [10].

Drivers might even think of driving as a distraction from other activities [11], and vehicle automation might be seen as a means of disengaging from driving, even when doing so violates the capabilities of the automation and compromises safety. Therefore, a major consequence of increasing automation might be the drivers' willingness to switch attention to non-driving tasks.

The evolving role of drivers in the context of automated driving and the additional activities drivers engage in present new challenges for evaluating how drivers work with the automation. Specifically, there are no standard scenarios and measures to evaluate joint control of the vehicle. This paper outlines a driving simulator evaluation protocol that captures driver engagement and disengagement in the driving task, and measures the safety margins achieved by drivers and automation.

Failure Modes of Driver-Automation Interaction

Central to assessing driver interaction with highly automated vehicles is the need to anticipate and test for likely failure modes. Risk analysis typically identifies failure modes associated with the mechanical, electronic, and software elements of systems and works to assure those risks remain below an acceptable level. Such risk estimates assume that drivers provide an additional safety margin, compensating for failures of the technology and other sources of unanticipated variability. This assumption is not always justified. Just as technology has failure modes, so do drivers and these failure modes should be assessed as part of a simulator-based evaluation.

Although highly automated vehicles lack operational exposure that might reveal prototypical driver-automation failure modes, experience in other domains suggests failure modes that might occur with vehicle automation. A very likely failure mode concerns drivers confusing Level 2 and Level 3 automation, where a critical distinction between these levels involves whether the driver has primary responsibility for monitoring the vehicle. *Responsibility diffusion* regarding whether the driver or the automation is primarily

responsible for vehicle monitoring and control is likely a prominent failure mode. People are poorly suited to the role of monitoring automation and are prone to over trusting and neglecting reliable automation [12,13]. *Mode confusion* associated with whether automatic control is engaged and if so what mode of control has been engaged is a prominent failure mode with automation in other domains and will likely affect vehicles equipped with combinations of Level 1, 2, and 3 automation [12,14, 15, 16, 17]. *Operating envelope awareness*, similar to the more degraded situation awareness that can accompany automation introduction, concerns awareness of the intended operating envelope and proximity to safety boundaries of this operating envelope. This failure mode will affect vehicle automation that is not intended to be used on all road types and in all road conditions [18, 19, 20]. *Ineffective transfer of control* represents a general failure mode that might occur during planned, unplanned, and unwarranted transfers of control from the automation to the person [17,21,22]. Unwarranted transfers of control are those situations where the automation sees no need for driver intervention, but the driver initiates a steering or braking maneuver that might conflict with the automation. These automation failure modes define the requirements for assessing vehicle automation.

No single assessment protocol will likely address all the possible driver-automation failure modes. Several previous automated driving studies have focused primarily on the failure mode of ineffective transfer of control. The objective of these studies was to determine how quickly drivers recognize and respond to safety critical events. An alert or warning was used to prompt drivers to regain control of the vehicle when the automation fails. The method for how and when drivers were informed of needed actions was implemented differently across studies. In some cases the warning time was varied across conditions [23,24]. Another study investigated driver response to one and two step processes to indicate a needed take-over [25]. This study also manipulated how drivers were alerted to the automation failure. The primary measure for these studies was the reaction time to begin the take-over process. Other driving performance metrics included minimum headway to lead vehicle, standard deviation of steering wheel position, and standard deviation of road offset (distance from the centerline of the road) for evaluating performance once the driver gained control.

Although many studies have focused on how and when control is traded, other automated vehicle studies have considered mode confusion failures and responsibility failure modes. These studies have examined driver behavior across different levels of automation. For example, manipulating the levels of automation (manual/fully automated) and traffic density (high/low) and drivers' willingness to overtake slow moving vehicles, management of car following, and secondary task engagement [26]. Similarly, drivers' response to automation was compared to an initial manual baseline condition [27]. When drivers experienced increasing levels of automation (i.e., lateral or longitudinal control followed by full automation) they were more willing to focus attention on secondary tasks as automation capability increased.

The following sections outline a protocol for addressing failure modes of responsibility diffusion, mode confusion, and operating envelope awareness. Another protocol is needed to address ineffective transfe