Use of High-Fidelity Simulation to Evaluate Driver Performance with Vehicle Automation Systems

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Abstract. Automation is an important tool for improving driver safety over the coming decades. Vehicle automation will tend to be implemented in stages with the intent of incrementally increasing the overall safety of driving through the reduction in crashes related to driver error. Driving simulators play a critical role in assessing the effectiveness of these new technologies. This paper discusses vehicle automation and provides several examples of the use of high fidelity simulators to evaluate new automation technologies in several different forms.

1 Introduction

Automation can be an important tool for vehicle designers in augmenting the capabilities of drivers to improve overall safety or efficiency. From an engineering perspective, automation is the best design solution when the human is incapable of performing the task or when automation can perform the task more safely or efficiently than the human operator can [1]. Special care in the design and implementation of automation must be taken to insure that the overall safety of the human-machine system is not reduced due to the addition of the automation. Automation, by definition, shifts the role of the human from operator to an increasingly supervisory position; the resulting transformation provides a challenging change in the relationship between the human and the system being controlled. Care must be taken in the allocation of function to carefully balance the assigned roles between the supervisor-human and the automated system [2]. Attention must also be paid to situations in which the operator is required to intervene rapidly when the automation fails. Keeping in mind the inherent limitations of the human operator, automation failure lends itself to situations where the operator is unable to accurately perceive the situation and respond quickly enough to prevent more catastrophic system failure.

When considering the fundamental purposes of automation in improving system safety and efficiency, there are clear benefits that can be realized in areas such as driving. The introduction of automation to vehicles has been studied for many years. Janssen et al. [3] have previously defined five stages in the evolution of automation in vehicle control, starting with navigational and longitudinal control at stage 1 and ending with full automation in stage 5. They, however, also warn that changes in driver behavior in response to increasing automation can ultimately reduce the potential

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safety gains that might be realized. As such, careful testing from the perspective of the combined human-machine system is necessary to fully understand the implications of each type of automation.

2 Vehicle Automation Systems

The concept of vehicle automation is not new and extensive prior research has already been undertaken. Work on vehicle automation was first presented to the public during the 1939 World's Fair in New York by General Motors (GM) [4]. Additional development work completed by GM on the driverless vehicle by the early 1960s demonstrated utility for robotic trucks. More recent studies conducted in the 1990s as part of the National Automated Highway System Consortium on full automation examined a number of critical issues associated with the automation of traffic [5]. Concurrent to these efforts, simulator studies examined the human factors issues surrounding use of automated lanes, including complacency and the entering and exiting of these dedicated lanes [6-8]. Although these research efforts showed that there was promise to vehicle automation, the research program ended in 1998. Since then, continuing research has shifted away from traffic automation to a greater focus on individually automated vehicles based on technology that could control the speed and headway of the vehicle, and other technology that could track the lane and maintain lane position. Research on these topics has included new advances into Adaptive Cruise Control[9]. Although much research has already been undertaken toward developing and deploying these systems, many research questions still need to be answered to allow continued development.

Janssen et al. [3] have defined one approach to classifying vehicle automation in terms of the stage of deployment that provides a useful framework for discussion. Specifically, they envision a process where development progresses from one stage to the next with the stages defined in **Table 1.** Although the stage approach proposed by Janssen et al. provides a logical approach to how automation is likely to be deployed in vehicles, it is clear that much of the development work has been undertaken concurrently. Some automated vehicle systems have already been deployed. They include such Stage 1 systems as Adaptive Cruise Control (ACC) that has been introduced into the vehicle fleet by companies such as Toyota, Nissan and General Motors; and navigation systems (including real-time traffic information) that have been deployed aftermarket by companies such as Garmin and Tom-Tom. Other systems starting to be deployed include Stage 2 technologies such as the SAVE-IT [10] concept by Delphi which monitors the driver and the environment to mitigate changes in driver state, as well other systems such as the Volvo Driver Alert Control and Lane Departure Warning. Even now, Stage 3 systems designed to control driver position in the lane using vision-based sensors are under development both independently and as an offshoot of lane departure warning systems. System designs for future developments in dedicated lanes and full automation have been ongoing since the 1990s [8, 11], but much more work is needed before their infrastructural and operational constraints can be sufficiently addressed.

Table 1. Stages of Automation [3]

Stage	Description
1	Navigation and Longitudinal Control
2	Integrated Systems as Co-Driver
3	Extension towards Lateral Control
4	Dedicated Lanes
5	Full Automation

Another classification scheme that can be used in parallel with Janssen et al.'s stages of automation defines three broad approaches to automation: augmented perception, augmented vehicle control, and overall vehicle control. Augmented perception is the foundation for most of the technologies that are used to provide control to the vehicle. The general approach is to use sensors to monitor the environment and provide alerts to the driver concerning situations of which the driver may not be aware such as the vehicle approaching the lane boundary or a braking lead vehicle. Augmented vehicle control is the vehicle providing assistance to the driver based upon sensor data to help the driver complete their intended maneuver. Example applications would include systems such as those designed to help maintain control when traction is reduced and systems that would provide assisted braking during an emergency brake response. Overall vehicle control addresses the total control of a specific aspect of driving rather than just assisting the driver. Example applications would include full lateral or longitudinal control, and ultimately full automation of the vehicle.

3 Applications of NADS Simulators to the Evaluation of Vehicle Automation

The National Advanced Driving Simulator at the University of Iowa is host to the NADS-1 simulator platform and fixed-based NADS-2 (see **Fig. 1.**). The NADS-1 is comprised of a 13-degree-of-freedom motion base with the largest motion envelope of any publicly available driving simulator in the world. The motion system's unique capabilities set it apart from other simulators, enabling the NADS-1 to accurately reproduce motion cues for sustained acceleration and braking maneuvers, movement across multiple lanes of traffic, and interaction with varying road surfaces that is not possible in fixed-base or limited-lateral-movement simulators. Fully instrumented car, sport utility vehicle, or truck cabs are mounted inside a 24-foot dome. The interior of this dome serves as the projection surface for the 360-degree photo-realistic visual display system. The cabs are instrumented to fully capture driver interaction while also providing configurable force feedback. Multiple in-vehicle cameras provide customized views of the cab environment. The NADS-2 utilizes the same architecture and vehicle cabs as the NADS-1, without the motion platform or the wrap-around visuals.

Since the NADS simulators became operational in 2001, they have been used for a variety of efforts to evaluate a range of transportation human factors issues, from driver behavior to cognitive change due to medication use to advanced vehicle systems[12]. Table 2. provides a list of research efforts that will be discussed in this

Fig. 1. (a) NADS-1Platform, (b) NADS-2 Platform

Table 2. Summary of NADS projects

Topic	Stage	Automation Approach	Type of Evaluation
Evaluation of driver/environment monitoring on driver performance	2	Augmented Detection	Proof of Concept
Electronic Stability Control	2	Augmented Control	Safety Benefit
Automatic Warning Modes for Night Vision Enhancement Systems	2	Augmented Detection	Design Concepts
Adaptive Cruise Control	1	Vehicle Control	Early Adopters

paper. These projects provide a cross-section of automation-related research that covers different types of automation and different study purposes. Each project in the table is defined in terms of the stage of automation, automation approach and the type of evaluation. In the discussion of these projects, it will be possible to explore how high-fidelity driving simulation can factor into the evaluation of vehicle automation.

3.1 Evaluation of Driver/Environment Monitoring System

This project served as one of several summary evaluations of the SAVE-IT[10] concept. The technology to be tested was designed to monitor and mitigate driver distraction in response to the proliferation of in-vehicle and carry-in technologies that drivers are now using. This technology would be defined as Stage 2 automation due to its intent to assist the driver through monitoring the environment and the driver's own state. When considering the automation approach, this technology can be clearly defined as augmented detection in that the system functionality is geared toward aiding the driver in detecting safety-critical situations through the use of its various sensors to detect potential lane departures and collisions. Driver state was evaluated using a vision based system that could detect when the driver was and was not attending to the driving environment. The type of evaluation undertaken can be defined as a proof of concept in that the evaluation focused on assessing the potential safety benefits of a prototype system.

This evaluation focused on the ability of the system to accurately detect when the driver is not attending to the driving environment and on the ability of the system to mitigate that distraction through changes to the in-vehicle display, providing earlier warnings when distraction is present, and suppression of false alarms when the driver was attentive. The alerts included visual, audio and haptic components. The study involved each driver completing three drives in which different implementations of the collision and lane departure detection algorithms were tested. Throughout each drive, the driver was periodically instructed to read incoming text messages and to identify a location on an electronic map. Both of these tasks were completed on an interactive system mounted in place of the radio on the center console.

The haptic component of the alert was the release of the throttle producing a subtle motion cue to the driver. Subtle motion cues of this type have been shown to be an effective component of in-vehicle safety systems due to their compatibility with the required reaction from the driver [9]. The high fidelity motion system of the NADS-1 is necessary to produce motion cues as subtle as a throttle release.

Results showed that drivers engaged in the tasks, but self-mitigated the distraction through chunking the tasks by glancing from the task to the roadway. Interview data indicated that some drivers attempted to anticipate when the system would provide alerts to minimize the number of alerts they received. This is an example of humans adapting behavior when automation is introduced. However, this was a single first-time use of the system. Different behavior may be seen with long-term use of similar automation. Drivers may be more willing to engage in riskier behavior, such as looking away from the roadway for longer periods and trusting the system to detect hazards they do not. Even upon first-time use, some interviewees' responses support this trend, noting that they chose to engage in the distracting task because they trusted that the system would notify them when they needed to shift their attention back to the roadway, see **Fig. 2.**

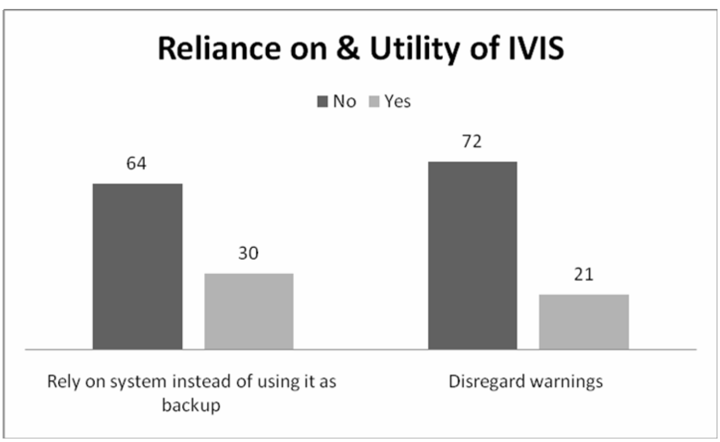

Fig. 2. Reliance on and Utility of In-Vehicle Information System (IVIS)

3.2 Electronic Stability Control Evaluation (ESC)

Electronic Stability Control (ESC) is an active safety system that detects when the vehicle is moving in a direction that differs from the intended direction. The system automatically triggers computer-controlled braking of the appropriate wheels or down-shifting to stabilize the vehicle and help the driver maintain control. It can be defined as Stage 2 automation in that it functions as an aide to the driver by monitoring and providing input when the system identifies a discrepancy. ESC would be defined as augmented control due to the fact that although the system intervenes to control the vehicle, it only does so in a limited way that aides the driver rather than replacing the driver control. The type of evaluation can be defined as a safety benefit analysis for existing technology.

NADS undertook one corporate-sponsored and two government-sponsored studies to examine the impact of ESC under various driving situations and road surface conditions. The studies examined crash rate on dry pavement, crash rate reduction on wet pavement, value of iconic indicators of system activation, and differential impact between types of vehicles. Study drives involved completion of avoidance, and curve negotiation maneuvers to assess the safety benefits of this technology. Across these studies, data were collected from more than 650 participants to assess the potential safety implications of this technology. Participants ranged in age from 16 to 74.

These evaluations of the ESC system required the ability to reproduce subtle cues that are present at the onset of loss-of-control situations. These subtle cues provide the early indications the driver needs to sense that the vehicle is in danger. Without these cues, drivers without an ESC system would be significantly hampered compared to the real world in their ability respond to these situations. Without realistic motion, the evaluation would likely over represent the benefits of the system. As such it was critical to use the NADS-1 due to the high fidelity motion cues it is able to generate.

Study results showed significant decreases in the crash rate across all vehicle types. In the first evaluation based on data from 120 participants [13], a significant reduction in loss of control was found with the system. Overall, there was an 88% reduction in loss of control with ESC present, when collapsing across all the data. The results of this study did not show any significant main effects for driver age or gender.

The two follow-on NHTSA studies provided additional data to the government for consideration in their rule-making role. These studies on wet and dry pavement continued to show reductions in loss-of-control associated with ESC technology in a variety of situations including both left and right avoidance maneuvers, curves, wind, and obstacle avoidance. Formal reports on the results for these studies are currently pending with NHTSA. Based in part on these research studies, NHTSA formulated rulemaking (Federal motor vehicle safety standard No. 126, 49 CFR Parts 571 & 585) that requires ESC in all light vehicles by model year 2012. NHTSA estimates that this technology could annually save up to 9,600 lives in the United States and prevent up to 238,000 injuries [14].

3.3 Adaptive Cruise Control Evaluation

Adaptive cruise control (ACC) is designed to provide longitudinal control of the vehicle. As with conventional cruise control, ACC maintains a set vehicle speed while driving; unlike conventional cruise control, ACC is also able to maintain a specified distance from a lead vehicle. The driver's longitudinal travel, therefore, is controlled by an algorithm that balances the set speed preference of the driver against the flow of traffic in the driver's lane. This automation technology can clearly be classified as Stage 1 automation. The automation approach would be defined as vehicle control as it is intended, once engaged, to fully control the speed and headway of the vehicle under the supervision of the driver. The type of evaluation that this study will constitute is an examination of the types of errors that early adopters make in use of the system in safety critical situations.

Developed as a precursor to fully-automated longitudinal travel, current implementations of ACC are mainly designated as convenience systems, not systems designed to improve safety. This is, in part, due to the infancy of the technology and the complexity of the task. ACC employs a vision-based system, using a radar or laser to determine the headway between the driver's vehicle and the lead vehicle. The system may fail if the radar or laser are occluded (e.g., from fog, dirt on lens), and because of the vision-system's angle of view, it may register vehicles in adjacent lanes or "lose" the lead vehicle on a curve.

Human error is also significant. Although ACC has been available as an optional or standard feature for the past decade, its availability continues to be limited to select luxury vehicles and thusly its deployment is limited. In a series of NHTSA and AAAFTS-sponsored early adopter reports [15-17], researchers found that although ACC has been well-received among early adopters, based primarily on its perceived convenience and improved safety, relatively few respondents fully understand how the system operates or, critically, the system's limitations. The lack of knowledge regarding ACC's operation presents challenges to safe vehicle operation: errors are made when users do not know when to take over from the automatic control, and users become less attentive to the driving task, more reliant on the automated system, and therefore less equipped to address time-sensitive critical driving situations that exceed the system's limits.

The purpose of the NADS ACC study[18] is to examine driver performance among users of ACC in order to discern usage and error patterns that could be addressed through empirically-grounded countermeasures. Critical to this evaluation is to recruit participants with sustained use of an ACC system. Of particular interest is: (1) the participant's reaction to feedback provided by the ACC system when its operational limits are about to be exceeded, such as in a rapid deceleration situation associated with an impending collision with a parked vehicle. Does the participant know how to accurately interpret the system's feedback and provide an appropriate and timely response? How does the participant balance the system's automation and their own control of the vehicle while driving?; (2) to identify driver usage patterns and error patterns that occur among drivers with ACC system experience, and attempt to link these patterns to their root causes. Errors caused by automation complacency and by system misunderstanding will be of special interest, as is the criticality of driver errors, and what impact they have on safety; and (3) to devise countermeasures based on expert feedback, relevant findings in the literature, and empirical data that have the potential to decrease the frequency and severity of errors or address problematic usage patterns.

The evaluation of the ACC system requires the ability to reproduce subtle cues indicating the acceleration and deceleration of the system. These subtle cues provide the primary feedback to the driver on the functioning of the system, without which the driver cannot accurately understand the systems current state. Similar to ESC, these critical system components of ACC require the high fidelity motion cues of the NADS-1.

3.4 Enhanced Night Vision Systems

Enhanced night vision systems are designed to provide the driver with critical visual information from the night driving scene that might not normally be available and to alert the driver when a pedestrian enters the driver's path. These systems aid the driver in identifying and avoiding pedestrians and potentially other hazards in the nighttime environment. This automation technology can be classified as Stage 2 automation due to its design intent to assist the driver through the presentation of additional information. The automation approach would be defined as augmented perception. The type of evaluation will be a design concept study due to the fact that the goal of the study is to provide design guidance concerning the choice of alert modality that might be effective, as well as defining a framework for additional system comparisons.

Night vision systems have been used for decades by the military to assist soldiers in nighttime maneuvers. Despite the widespread military use, this technology has not garnered widespread use in automobiles. Initial implementations in automobiles provided the driver with only the infrared signatures from the environment without the threat warnings that are currently being implemented. Current technology allows these systems to differentiate between a target in the environment and a threat to the driver. Tsuji et al. [19] provide an excellent summary of the system approach that is under evaluation.

This study[20] will examine the effectiveness of various alerting modalities on the ability of the driver to respond to pedestrian threats. Tsuji et al. [19] reported that 68% of all pedestrian fatalities occur at night, 90% occurred while the driver was traveling straight ahead, and that 78% occur when the driver is traveling greater than 40 km/h. These statistics point to a general difficulty with identifying and responding to a pedestrian quickly enough to avoid hitting them, which night vision systems with target warning should be able to help address.

A critical question in the development of these systems remains what is the best way of alerting the driver to the presence of the potential threat. As the events to which this system would alert the driver are relatively infrequent, identifying an alert mechanism that can effectively warn the driver of the threat in such a way that they can safely respond is critical. Options under consideration include a visual alert on the display indicating a threat, an auditory tone, and seat vibration. The ultimate aim will be to provide appropriate guidance to NHTSA on the utility of visual, auditory, and tactile warnings as part of enhanced night vision systems.

Although this study requires high-fidelity visuals to provide an accurate understanding of the driver's ability to detect targets in the night driving scene and to provide the infrared display, there is not a compelling need for motion cueing to assess this technology. This study will, therefore, utilize the NADS-2 simulator rather than the full motion NADS-1. As the system being tested is forward looking only, this an ideal match between the needs of this study and the NADS-2.

4. Conclusions

Vehicle automation will become an increasingly important tool for vehicle designers in a continued effort to improve overall safety on our nation's highways. Each stage of automation provides different types of safety benefits. As the implementation of automation progresses beyond the Stage 1 and 2 automations that are currently being deployed, drivers will be increasingly moved to more supervisory roles. This has the potential to reduce crashes by reducing the potential impact of the greatest cause (human error); however, there is a risk that this transition will lead to more severe crashes when they do occur. Stage 3, 4, and 5 automations are linked to needed technology advances in lateral and route control. Once these advances are in place, it should be expected that automation in these stages will be quickly developed in response to drivers' desire for increased convenience and an overarching goal of reducing crashes. Special care is and will continue to be needed in the evaluation of automation technologies across all five stages to insure that a net safety benefit will occur through the addition of the automation into the driver-vehicle system.

Driving simulators can play an important role in the evaluation of these technologies. Simulators of different fidelities play unique roles in this, with lower fidelity simulators being used earlier in the design phase, and higher fidelity simulators being used to provide more definitive answers later in the process. High fidelity simulators such as those located at NADS allow for nearly full immersion in the driving environment that is as close to real world driving as is possible in a simulator. For many research efforts, the ability to provide valid motion cueing to the drivers is critical to achieving realistic driver responses that can be used to accurately assess safety critical system. High fidelity driving simulation environments, particularly those provided at the National Advanced Driving Simulator, offer the opportunity to test a variety of automation systems to assess the potential safety impact in a manner that is both safe and reliable. The value of these types of assessments is most clearly demonstrated by the Electronic Stability research conducted in the NADS-1.

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