Driver Distraction Is More than Just Taking Eyes off the Road

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INTRODUCTION

Cars are not simply for driving anymore. For some they serve as mobile offices; for others, mobile entertainment centers. While there have always been distractions present such as the external environment, passengers in the car, and simple wandering attention, today’s drivers and vehicles can sometimes present significant additional distractions if not managed properly. With technology such as Bluetooth accessories, MP3 players, DVD players, GPS systems, and various other infotainment and comfort devices, one thing is clear: These devices provide the opportunity for more distractions from the driving task.

Today’s driver is generally concentrating on a lot more than just driving. There is a growing concern that all of these potential distractions may lead to increases in the likelihood of accidents. In the last three years, two National Distracted Driver Summits were held in Washington, DC where driver distraction was discussed in detail. In response to the driver distraction problem, some states have passed legislation restricting the use of cell phones in vehicles, but these laws only begin to scratch the surface of the possible effects of emerging potential means of distraction.

A broad attempt aimed at understanding the behaviors of the modern driver from a human factors perspective was the 100-car study. This was a massive and novel undertaking aimed at assessing driver behavior in the moments leading up to an incident or crash in a real environment. The videotape data collected in this study indicated that in many instances, drivers were looking away from the road in the moments before an incident or crash. This has led to a popular opinion that looking away when an event occurs is the principal cause of distraction-related crashes. The data from the 100-car study and other epidemiological undertakings certainly support this point; however, as we detail below, there are many other important distraction-related performance effects that do not solely involve eyes off the road and glance behavior.

LOOKING BEYOND EYES OFF THE ROAD

Some of the most convincing evidence that there is more to driver distraction than just glance behavior comes from the work of Strayer, Drews, and Johnston. They conducted three driving simulator experiments where they had participants naturally converse with confederates about various topics. They used a car-following paradigm and measured responses to lead car-braking events. Braking reaction times were significantly slower in the hands-free cell phone condition as compared to the no-task condition, suggesting that simply conversing negatively affected driver ability to brake. More interestingly, a recognition post-test showed that participants in the cell phone condition recognized fewer billboards and road signs than those who were just driving. Concurrent eye-tracking data revealed that people actually did look at the signs in both conditions (no-task and cell phone) with similar frequency, but the probability of recognizing a sign that they had fixated on was significantly smaller in the cell phone condition than in the no-task condition. In a fourth experiment, Strayer et al. tested whether the location of the billboards had affected recognition. They used a pursuit-tracking task and presented words in the center of the screen during the tracking task. Once again eye-track data showed that participants fixated on the words in both conditions but were slower to recognize the words in the cell phone condition as compared to the no-task condition. Overall these results show that even if a distraction allows the driver to keep eyes on the road, there still may...
be other negative effects. Furthermore, these results provide an excellent example of a distraction-related performance decrement that is not associated with looking away from the road. Both slower reaction times (Experiment 4) and looking without seeing (Experiments 1-3) could easily lead to crashes or incidents while driving, even though the driver’s eyes would be on the road during the critical events. This is strong evidence that there is much more to evaluating driver distraction-related performance effects than just examining glance behavior. In these experiments, people were actually looking at something and still do not “see” it due to the fact that they are distracted. It is important to point out that this does not rule out the idea that it is essential to see critical events as they occur, but it does show that there are mechanisms other than physically not fixating on the roadway that can lead to drivers not processing and/or remembering visual information.

Distractions Affect More Than Glance Behavior

Focusing solely on glance behavior in trying to understand the distraction-related causes of crashes and incidents omits numerous other related variables, with the inattention blindness causing impairment in perceptual memory and as a result creating a situation where even when drivers are looking forward on the roadway, they may not be able to perceive information presented. Other research has shown that distracting events can lead to greater non-response rates to critical traffic events. Participants viewed video of traffic situations and were asked to respond to various critical events such as speed changes (acceleration or braking), swerving, or lane changing. They performed this in either a single-task condition or while performing some other distracting task. The distracting tasks were either hands-free cell phone conversation of various intensities or manipulating the radio. All distractions led to increases in non-responses to the critical events. Interestingly, as the cell phone conversation became more intense, the non-response rates increased. Although not explicitly mentioned, it can be inferred that in the hands-free cell phone tasks participants were looking at the screen and that the mere presence of another task made it more difficult to respond to critical traffic events. These findings remain consistent with the idea that even if distractions do not draw visual fixation away from the road, they can still lead to poorer driving performance and increase the risk of a crash or incident.

Further evidence of people’s poor ability to perceive and/or encode events while distracted comes from two studies examining the effects of distractions on drivers’ abilities to choose safe gaps for crossing or turning into through traffic. Brown, Tickner, and Simmonds used an on-road methodology to assess the effects of hands-free telephoning on general driving abilities and specifically on gap acceptance. Drivers were required to make decisions about whether or not to pass through gaps of different size set up through the driving course. In addition, their driving behavior in relation to lane and speed maintenance was also assessed. Brown et al. found that, during telephoning, drivers were more likely to attempt to go through gaps that were too small for the car to fit through than they were in the single-task driving decision. In addition, they maintained slower overall speeds. These findings were further corroborated more recently by Cooper and Zheng, who showed that distracted drivers made less safe gap judgments in a left-turn through-traffic scenario. In the single-task version of this scenario, they determined that people used gap size, speed of oncoming vehicles, road conditions, and weather to make informed decisions about whether to attempt a left turn. When distracted, however, drivers failed to utilize all available information and made riskier decisions as measured by smaller mean time to collision.

This evidence suggests that even though participants saw the gaps and attempted to make an accurate judgment about them, the distraction impaired their ability to do so. It is clear that some visual input may not be perceived or may be perceived but not encoded. This occurs despite the fact that the gap judgment paradigm forces people to process the information (gap size) and make a decision. Where previous work suggested that distraction may cause problems in the perception of information, these studies point to distraction-related impairments in the encoding, process, and/or decision-making aspects of task performance. It is not clear from these studies whether distraction disrupts the perception or encoding phase of information processing, but it is clear that distraction impairs performance on the gap-acceptance task even when people are looking at the road. Additionally, the slower speeds maintained in the telephoning condition suggest that drivers may have been attempting to employ some compensatory behaviors to reduce the difficulty added by the distracting task. These findings further support the idea that distracted drivers do not necessarily have to be looking away during a critical event to be at higher risk for a crash or other incident.

The 100-car study suggests that the coincidence of eyes-off-road and critical events may be the primary cause of distraction-related crashes. It is clear from the evidence presented that there are other variables and phenomena unrelated to gaze behavior that are important to consider in determining the causes of distraction-related crashes. It may seem as though gaze has been treated as a binary variable—either your eyes are on the road or off the road—but this is far from the case. Harbluk, Noy, Tribovich, and Eizenman and Recarte and Nunes have both...
shown that even though distraction does not necessarily remove eyes from the road, it can change glance behavior in other ways that have damaging effects to driving. Harbluk et al.6 showed that secondary tasks caused drivers to make fewer glances to the periphery, rear- and sideview mirrors, intersections, traffic lights, and other traffic cues. They showed that even though a driver’s eyes may be on the road during a critical event, he or she may simply fail to maintain eye fixation on critical elements of the roadway environment.

The findings of Harbluk et al.5 follow the pattern of a similar phenomenon called cognitive tunneling.6 Recarte and Nunes7 did not simply focus on where drivers were looking at the time of a critical incident; rather, they examined the total area of inspection during a driving task. They found that when operating in heightened workload conditions (such as while distracted) drivers examined a smaller total area of the surrounding environment. This area was still centered on the roadway, but drivers who were under high-demand cognitive workloads from phone conversations make fewer glances away from the central area of the roadway.

This is another example of a distraction-related driving impairment that does not take the eyes off the road during a critical event but could still cause that critical event to be missed.

NOT JUST CELL PHONES

An additional aspect of driver distraction that is not accounted for by looking at glance behavior is the type of distraction itself. Much attention has been given to the distracting effects of cell phones and, as many of the studies mentioned above have shown, cell phones do lead to worse driving performance, regardless of where people may be looking.4–5 Laberge, Sciabba, White, and Caird8 showed that it is not necessarily the physical manipulation of a cellular device that causes the distraction, but it may be the simple act of conversing. They compared the distracting effects of conversing over a cell phone versus conversing with an in-car passenger and found that both conditions led to slower reaction times to respond to critical events. They also found that subjective ratings of workload were higher in all conversation conditions as opposed to driving alone. These findings suggest that heightened workload may be another important factor to take into account when assessing the state of the driver and vehicle at the time of a critical event. If a driver is experiencing high workload in coincidence with a critical event on the road, it may not matter where the driver is looking—a crash or incident may occur.

DISTRACTIONS AND WORKLOAD

Most of the research discussed to this point has focused on the effects of distracting tasks on people’s ability to drive while their eyes are on the road. Another approach to understanding the relationship between eye gaze and driver distraction is to examine the role of different driving environments on drivers’ abilities to perform secondary tasks. This approach was used by Jahn, Oelhme, Krums, and Gelau9 to assess drivers’ tendencies to examine their periphery while driving. Participants drove on either urban (high-workload) or rural (low-workload) roads while performing a peripheral-detection task. They found that on urban roads drivers performed worse on the peripheral-detection task, suggesting that if a critical event were to occur in the periphery during a high-workload drive, there would be a good chance that the driver could miss it even if his or her eyes were on the road. This is another example of a situation in which simply having eyes on the road would not be sufficient to avoid an incident or crash. Critical driving events certainly can occur in the periphery, and if drivers are failing to scan this area, there will be a higher occurrence of incidents and crashes, even if their eyes are on the road. These results were further corroborated by Liu and Lee,10 who showed that it was possible to increase workload by either increasing driving demands or increasing secondary task demands. Both of these cases resulted in impaired performance on both the driving and secondary tasks.

Lastly, it is important to look at other contributing factors that may affect driver performance. In addition the coincidence of eyes-off-road and critical events, another major finding of the 100-car study was that fatigue plays a large role in exacerbating poor driver behavior.1 The videocassette data show that while fatigued drivers did keep their eyes on the road, they were more vulnerable to improper, slower, or no reactions to critical events leading to incidents or crashes. Overall, it can be seen that any type of distraction—regardless of glance direction—can have large consequences if it coincides with a critical driving event.

CONCLUSION

We feel that the results we have discussed demonstrate the significant potential for eyes-off-road distraction-related driving impairments. It should be clear now that eyes-off-road phenomena are not sufficient to explain all distraction-related incidents and crashes on the road. We have discussed many other factors that do not necessarily take the eyes off the road but that do contribute to distraction-related impairments in driving performance. For example, distracted drivers whose eyes are still on the road do not necessarily perceive and/or encode objects they fixate on,2 are more likely to not respond to traffic events,3 make more risky judgments of how to proceed safely through gaps and
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References

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Though much work has been done, the need for research and understanding of the effects of distraction on driving has never been greater. With a population ever hungry for connectivity and with more technology being integrated into vehicles, the potential for drivers to become distracted is rising quickly. Despite the current legislation and potentially deadly consequences, certain drivers routinely drive distracted—with a phone in hand, with eyes off the road, or while engrossed in other activities—exposing themselves and other motorists around them to greater accident risks.

This article is aimed at helping to explain the types and common effects of driver distraction. The information presented here will equip readers with the information necessary to aid clients in
achieving a better understanding of the implications of driver distraction on their businesses and litigation efforts.

**Distraction Comes in All Shapes and Sizes**

Generally, there are three different modalities from which distraction can arise: visual, manual, and cognitive. Visual distraction occurs when activities unrelated to the primary task of driving result in a driver’s gaze shifting away from the roadway. The effects of visual distractions can range from simply missing landmarks or signs, to drivers not seeing a vehicle stopped directly in front of them. David Strayer et al., *Cell Phone-Induced Failures of Visual Attention During Simulated Driving*, 9 J. of Experimental Psychol.: Applied 23-32 (2003). Something as routine as changing the temperature in a car can be a visual distraction if a driver glances down at the dial or display. Most visual distractions in a vehicle are short-lived. Previous research has shown that the average glance duration off the roadway to most in-vehicle comfort and infotainment systems is less than a second or two. Paul L. Olson et al., *Forensic Aspects of Driver Perception and Response* (Lawyers & Judges Publ’g Co., Inc., 3d ed. 2010). Other routine activities, such as monitoring children in the back seat of a vehicle, can lead to highly variable and sometimes lengthy visual distractions. Jane D. Stutts, Ph.D. et al., AAA Foundation for Traffic Safety, *The Role of Driver Distraction in Traffic Crashes* (May 2001), http://www.safedriver.gr/data/84/distraction_aaa.pdf (last visited Oct. 30, 2013).

More recently, activities requiring longer and more frequent glances off the roadway, such as text messaging, have become more prevalent in the vehicle. For example, when changing the temperature in a vehicle, a driver can usually perform this action in about three short glances away from the roadway. Thomas Dingus, Va. Polytechnic Inst. & St. Univ., *Human Factors Tests and Evaluation of an Automobile Moving-Map Navigation System. Part I. Attentional Demand Requirements* (1986). Using display oriented technologies such as GPS navigation systems or smartphones for tasks such as emailing, web-browsing, and text messaging might require many more glances away from the roadway than a typical in-vehicle task (for example, changing the radio, adjusting the temperature, etc.). Even though each single glance while composing a text message may be on the order of a second or less, the cumulative effects of many glances means that the driver’s eyes are off the roadway for a longer total time as compared to the more mundane tasks requiring only a glance or two. Robert E. Dewar & Paul L. Olson, *Human Factors in Traffic Safety* (Lawyers & Judges Publ’g Co., Inc. 2002), http://www.lawyersandjudges.com/client/client_docs/5473_traffic_errata.pdf.

Manual distraction results from completing any in-vehicle action that requires removing one’s hand or hands from the steering wheel in support of a non-driving related task. As with visual distractions, manual distractions include tasks that drivers might view as commonplace or even as part of their normal driving experience. Manually distracting tasks may include changing the radio or climate control, eating and drinking, smoking, or operating an infotainment device, such as a cell phone or GPS. Often, manual distractions are in concert with visual distractions. For example, when changing the radio station, drivers tend to look at the radio while moving their hands there as well. As with visual distractions, the greater the frequency and the greater the duration of the distraction, the more likely it will be deleterious to the task of driving.

Understanding how visual and manual interactions with non-driving-related in-vehicle tasks can be distracting is often relatively straightforward—eyes off the road and hands off the controls, respectively. Although research on the third mode, cognitive distraction, has been increasing recently, this form of distraction is sometimes overlooked or misunderstood during incident investigation. McKnight & McKnight, *supra*; Strayer et al., *Measuring Cognitive Distraction, supra*; David Cades et al., *Driver Distraction Is More than Just Taking Eyes Off the Road*, 81 ITE J. 26-33 (2011); and Miguel Recarte & Luis Nunes, *Effects of Verbal and Spatial-Imagery Tasks on Eye Fixations while Driving*, 6 Journal of Experimental Psychology: Applied 31-43 (2000). Unlike visual and manual
modes of distraction, which are objectively observable, cognitive distractions can affect driving performance while the driver’s hands are on the wheel and eyes are on the road.

Any time that even a portion of a driver’s cognitive resources are focused on something other than the driving task, that driver is experiencing some level of cognitive distraction. Cognitive distraction captures anything from thinking about what you need to do when you get home to having an emotionally charged conversation on a cell phone. As with visual and manual modes of distraction, both the frequency and duration of cognitive distraction affect the likelihood of it having negative effects on the driving task. For instance, a drawn out, attentionally demanding phone conversation can result in distraction-related driving impairments for a longer period of time than leaving a simple voicemail.

Cognitive distraction is not only due to cellphone conversations. Research has shown that in-vehicle conversations, day dreaming, and simply talking or singing alone in a car may increase the risk of an incident while driving. Neale et al., supra. In this sense, attention to and distraction from the driving task exists along a continuum. Understanding the types and magnitude of distraction is required in order to assess the presence of distraction, its relevance to the immediate driving performance, and its contribution to an accident.

**What Are the Effects of Distraction on the Typical Driver?**

When approaching any case in which driver behavior may be called into question, exploring and understanding the potential sources of driver distraction may be critical. As with describing the modes of distraction, some of the effects of driver distraction are more straightforward than others. For example, if a driver is looking at the radio when a bicyclist crosses in front of his vehicle, that driver is unlikely to see the bicyclist. In such a case, the distraction of looking at the radio led to the driver’s eyes being off the road and to the driver not seeing a potential hazard. Similarly, with a manual distraction, if an unexpected hazard requires the driver to enter a steering input, shift the gear, or pull the emergency brake and his hands are off the wheel adjusting the climate control or reaching for a drink in the cup holder, then the required physical response will be delayed or might not occur at all. Dingus, supra. These types of distractions can have a clear deleterious effect on driving performance if a driver’s eyes are off the road, or hands are off the wheel at a time when that driver would need eyes on the road and hands on the wheel.

Assessing the effects of cognitive distraction, and possible case-relevant arguments that can be made as a result thereof, is a slightly more nuanced and intricate endeavor. Simply because a driver has his hands on the wheel and eyes on the road does not mean that he is not susceptible to driving impairments due to distraction. Research has shown that cognitively distracted drivers might not be able to perceive information presented to them visually even if they are looking right at it. Strayer et al., *Cell Phone-Induced Failures*, supra. These types of distraction can also lead to slower responses to hazards in the roadway, higher non-response rates to critical events or hazards in the roadway, decreased ability to safely negotiate gaps in traffic to drive through, and decreased scanning behavior, just to name a few. Strayer et al., *Measuring Cognitive Distraction*, supra; McKnight & McKnight, supra; Brown et al., supra; Peter J. Cooper & Yvonne Zheng, *Turning Gap Acceptance Decision-Making: The Impact of Driver Distraction*, 33 J. of Safety Res. 321, 321-35 (Oct. 2002); and Recarte & Nunes, supra.

As the proliferation of in-vehicle devices and tasks continue to inundate drivers with potential sources of distraction—visual, manual, and cognitive—investigators and litigators alike must be sure to assess the human factors associated with these sources of distraction in order to get a complete picture of what might have occurred.
What Can We Do?

Sights, sounds, tasks, and goals compete for our attention and cognitive resources on a regular basis. When this occurs during a complex, dynamic, and demanding task such as driving, momentary lapses and distractions can have profound effects on safety. Not all shifts of attention are the same, however, nor would one expect them to have similar consequences. Decades of research in human factors and cognitive engineering have helped categorize the types and frequency of such distraction. More recently, scientific investigations have begun to quantify the variety of effects these distractions may have on driver behavior.

A technical understanding of distraction, rooted in scientific investigations of human perception, cognition, and behavior, allows one to make sound assessments of the role a driver’s actions may have played in the causation of an accident and strategic decisions as to handling one’s case. Additionally, such an understanding can aid companies in training their drivers on both the hazards and safe uses of the rapidly proliferating technology. While no employer can ever ensure a driver will not violate company policy while unsupervised on the job, providing the proper training and guidelines for use of in-vehicle technology can reduce risks and thereby increase driver, and company, safety overall.

Finally, the choices of organizations to adopt new administrative policies for in-vehicle devices, hardware, or software that locks out cellphones while moving, or employee training with a goal of educating employees on the risks of distracted driving should be studied thoroughly by experienced and qualified human factors specialists and assessed on a case by case basis before assuming they will have an overall reduction of risk on the road. Policies and practices that are perceived as too restrictive may entice some employees to search for ways to work around the restrictions. Implementation of hardware, training, and enforcement of policies may have unintended secondary consequences.

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Abstract

Advanced Driver Assistive System (ADAS) technologies have been introduced as the automotive industry moves towards autonomous driving. One ADAS technology with the potential for substantial safety benefits is forward collision warning and mitigation (FCWM), which is designed to warn drivers of imminent front-end collisions, potentiate driver braking responses, and apply the vehicle's brakes autonomously. Although the proliferation of FCWM technologies can, in many ways, mitigate the necessity of a timely braking response by a driver in an emergency situation, how these systems affect a driver's overall ability to safely, efficiently, and comfortably operate a motor vehicle remains unclear. Exponent conducted a closed-course evaluation of drivers' reactions to an imminent forward collision event while driving an FCWM-equipped vehicle, either with or without a secondary task administered through a hands-free cell phone. Participants drove the vehicle along the test track at a speed of 35 mph 40 feet behind an inflatable target vehicle, which was towed behind a truck and, unbeknownst to drivers, released at one point during the drive to simulate a sudden lead-vehicle braking event. Despite the relatively high speed and short headway, 14 of 16 participants were able to respond before the autonomous braking system engaged. The audiovisual collision warning system activated for 11 participants; of these, 7 reacted before the warning began. These preliminary results indicate that although ADAS technologies, specifically FCWM, can be effective tools to mitigate the risk and severity of a collision, attentive driving continues to play an essential role in roadway safety.

Introduction

The landscape of the driving experience is changing. It was not more than 15 years ago when having electronic stability control (ESC) in a vehicle was considered a luxury feature; as of 2010, ESC was a standard feature in approximately 85% of new vehicles [1], and this number is only expected to grow. The automotive community is currently engaged in an evolution of automated vehicle technologies towards the goal of ubiquitous autonomous vehicles in communication with roadways and infrastructure [2]. Some fully autonomous vehicles and infrastructure have already been realized in the form of self-driving vehicles from Google, BMW, Volvo, Audi, Cadillac, Ford, GM, Tesla, Nissan, Toyota, Volkswagen, and Mercedes-Benz [3], and “smart” stretches of highway in Virginia [4] and California [5, 6]. In the interim, other technologies collectively referred to herein as Advanced Driver Assistive Systems (ADAS) are being introduced to automate various aspects of the driving task to improve driver safety. These technologies include adaptive cruise control, lane departure warnings and correction, back-up cameras and warnings, and parking assistance systems. ADAS technologies which automate vehicle functions normally controlled by the driver are hoped to reduce or eliminate driver error, and thus prevent a large number of accidents [2].

One ADAS technology that has the potential to bring significant safety benefits is forward collision warning and mitigation (FCWM; see [8]). FCWM systems are designed to 1) warn drivers of imminent front-end collisions, 2) potentiate driver braking responses, and 3) in the absence of driver response, apply the vehicle's brakes autonomously to slow or, in some cases, stop the vehicle prior to a forward collision. Studies suggest that compared to vehicles without FCWM systems, insurance claims were approximately one-quarter less for vehicles equipped with FCWM and autonomous braking in the first few years they were on the market [9, 10]. Other studies suggest that FCWM systems can react faster and/or decelerate the vehicle faster than drivers alone can [11, 12]. As of 2011, FCWM systems that warn of potential collisions, support braking, and/or automate braking are present in certain models of at least 19 different automakers [10].
Driving with Autonomous Vehicle Systems

The task of driving has become increasingly distributed between the driver and the vehicle as ADAS technologies evolve. To date, very little research has examined the performance of both driver and vehicle responding to emergencies jointly, and even less research has examined such responding on the road rather than in a simulator. Notable research efforts include several large-scale field operational tests in Europe (e.g., EuroFOT) [13] and in the United States (e.g., ACAS FOT and IVBSS FOT) [14, 15]. However, such efforts result in limited data on driver and vehicle performance such as FCWM, as real-world emergencies are rare under non-experimental conditions. Furthermore, newer FCWM systems are improved in terms of false alarm rates (although still prone to them) and more prevalent in the consumer vehicle arena, suggesting a renewed opportunity for research into driver-FCWM interaction. Such research is necessary for several reasons. First, it is instructive to know how drivers actually utilize the inherent vehicle capabilities and ADAS technologies in everyday driving and emergency situations. Similarly, with the proliferation of ADAS technologies, significant feedback from one technology may obviate others; for example, forward collision or lane departure warnings may be sufficient to induce a change in driver behavior and thus preclude engagement of autonomous systems. Third, driver trust in autonomous vehicle systems, based on system performance, will determine their acceptance as drivers choose whether or when to give increasing control of the vehicle to these automated systems [2, 16].

Driver Inattention and Situational Awareness

Existing studies of autonomous systems in vehicles indicate that the systems are very effective for simple driving tasks, but when the systems break down or reach their limits, drivers are often not able to take over in a timely manner [17, 18]. Such failures in driver response are likely while drivers are engaged in secondary tasks [19], which occur readily with increased vehicle automation [20]. For example, Carsten et al. gave participants the option to play games, read, eat, do a puzzle, watch a DVD, listen to the radio, or groom while driving either with a lane departure warning system, with autonomous lane keeping, or with adaptive cruise control [20]. They found that participants opted to shift their attention away from the driving task with increased in-vehicle automation, particularly with autonomous lane keeping [20].

Driver distraction and inattention are common causes of accidents in vehicles generally [21]. Distractions can be classified as either cognitive (e.g., a hands-free cell phone conversation), visuo-motor (e.g., manipulating in-vehicle controls), or a combination of both (e.g., hand-held cell phone conversation) [22]. Numerous scientific studies demonstrate that all of these types of distractions can cause decrements in driver perception and performance. Even cognitive tasks without a visuo-motor component (performing mental arithmetic, voice-dialing) have been demonstrated to affect drivers' visual behavior, causing them to look less at the periphery, at in-vehicle instruments/mirrors, and at traffic signals compared to when just driving [23]. This change in driver visual behavior leads to diminished situational awareness, and increases the likelihood of missing otherwise conspicuous visual cues such as lead vehicle brake lights [22, 24, 25].

Disengagement from the driving task makes it difficult for drivers to respond in sudden emergencies because they are “out-of-the-loop” [26]. For example, simulator studies have found that drivers spend less time gazing at the road ahead [20] and exhibit increased reaction times [7] when parts of the driving task are automated. Consequently, it has been suggested that more effective ADAS technologies are those that involve the driver being in control of the vehicle, and which support driving functions rather than fully automating them [27], or which alert the driver to situations in which the technology may be more unreliable [28].

Risky Driving Behavior

Other researchers have found that drivers who remain engaged in the driving task may practice riskier driving behaviors in the presence of autonomous systems, presumably because they believe the systems will counteract their behavior. For example, drivers have been observed to increase their speeds [12, 19], decrease headway [14], yield to other traffic less often, and decrease control of lane position [7]. However, even in the presence of riskier driving behaviors, Muhrr et al. found in their study of FCWM with autonomous emergency braking that the vehicle responded as quickly as attentive drivers without autonomous braking, suggesting the strength of the systems' safety benefits in situations in which a driver may be distracted or otherwise inattentive [12].

Degrees of Automation

FCWM presents a unique opportunity to evaluate varying levels of automation at once. Levels of automation are preliminarily defined by NHTSA [29] according to the ratio of driver-to-vehicle control of the driving task. These levels range from no automation (Level 0) to combined function automation in which more than one vehicle function is automated but the driver remains responsible for monitoring the roadway (Level 3), to fully autonomous vehicles requiring no driver input (Level 5). Similarly, Parasuraman et al.'s model of automation separates automated functions based on the stages of information processing, including information acquisition, information analysis, decision selection, and action implementation [30]. For example, information acquisition may involve sensors that identify the speed limit posted on roadsides, whereas information analysis may involve speed warnings on the dashboard if the speed limit is exceeded. Decision selection may be automated by preparing the vehicle to potentiate a driver's response; for example, by lowering thresholds for driver brake or steering input. Finally, action implementation may be automated by the vehicle performing an evasive maneuver or corrective action, such as slowing the vehicle to the speed limit, without driver input. These stages place the driver along a continuum: Information acquisition requires the driver to understand the meaning of the information as well as choose and perform actions based on that information, whereas action implementation requires nothing of the driver. FCWM embodies several of the stages, including the vehicle as providing information to the driver with the driver still as main decision-maker (i.e., audio/visual warnings; analogous to information acquisition and analysis); vehicle and driver collectively executing a decision (i.e., potentiating braking; analogous to decision selection); and, finally, the vehicle making the decision (i.e., autonomous braking; analogous to action implementation).
Present Research

The proliferation of ADAS technologies is leading to a change in the relationship between driver and vehicle, and as this relationship evolves, there is a need for continued and expanded human factors investigation to understand how the presence and use of these technologies affect a driver's ability to safely, efficiently, and comfortably operate a motor vehicle. In an effort to understand how drivers in vehicles equipped with FCWM respond to imminent collision situations, we utilized a vehicle with FCWM on a closed course test track to conduct an evaluation of driver reactions to an imminent forward collision event, either while drivers were performing mental arithmetic via a hands-free cell phone or while they were performing no secondary task. We specifically examined driver behavior during different stages of FCWM (i.e., from audiovisual collision warning to autonomous vehicle braking) and the effects of secondary task performance on responses to an emergency while in the presence of an autonomous vehicle system. The present results support and contribute to the existing literature on driver use and acceptance of ADAS technologies as well as the real-world benefits of FCWM to roadway safety.

Methods

Participants

Twenty-two participants (13 female; mean age: 43.8 years old) were recruited from the community surrounding Exponent's test track facility in Phoenix, Arizona. All participants were over the age of 18 (age range: 21-61 years old) with a valid driver's license and with normal vision or corrected-to-normal vision. Potential participants who reported that they drive vehicles equipped with FCWM technology and/or autonomous braking were not eligible to participate. The first six participants served to pilot the testing procedures and experimental conditions. Participants were compensated with $100 in exchange for their participation.

Test Vehicle and Instrumentation

The test vehicle used was a 2014 luxury sedan equipped with an FCWM system. This system utilizes the vehicle's radar, laser, and optical sensors to monitor the road ahead for slow-moving objects. When the system detects a hazard ahead it provides an audible collision warning, projects a flashing visual collision warning onto the driver's side windshield, and pre-charges the brakes to potentiate driver response. If the system determines a collision is imminent and does not detect sufficient driver response, the system will slow or stop the vehicle with full braking force. Prior to beginning the study, the test vehicle's FCWM system was tested and confirmed to respond to the target vehicle as expected based on the description of the system in the vehicle's documentation and in vehicle literature. The system was subsequently tested at the completion of the study to confirm consistent functioning over time.

Video data of participant responses were recorded from four cameras situated in the locations shown in Figure 1. The video data allowed for the estimation of driver foot pedal responses as well as vehicle speed. Additionally, brake pedal loading, steering wheel angle, GPS coordinates, and speed data were collected from the vehicle's CAN recorder and a precision GPS system mounted in the back seat of the vehicle. A more detailed description of the test vehicle and instrumentation can be found in Crump et al. [31].

Test Track

The test track consisted of a private, closed-course, two-mile paved road and skid pad (see Figure 2), and required participants to follow normal traffic laws, including a speed limit of 35 mph on the straight portion of the test track and 20-25 mph on the curved portion of the test track (i.e., the skid pad). The direction of travel as well as the location of stoplights and a stop bar are indicated on Figure 2.

Procedures

Participants were initially shown the vehicle, and the driving task was described to them prior to getting into the vehicle and preparing to drive. For participants in the secondary task condition, the experimenter began by connecting the study cell phone to the vehicle's on-board hands-free Bluetooth system and completing a test call. The experimenter then calibrated the data collection equipment. Following calibration, the experimenter read a list of vehicle features, including the full suite of ADAS technologies present on the vehicle, to the participant and answered any questions. Participants completed a total of three laps around the test track: one for practice, one that included a path around the skid pad, and one following a lead vehicle around the test track for the balloon car incursion event. When behind the lead vehicle, participants were asked to maintain a speed of 35 mph and a headway of 40 feet to attempt to reduce the time available to react to the lead vehicle braking event. Half of the participants...
were randomly assigned to complete the drive while simultaneously completing a secondary task, which consisted of mental arithmetic, on the hands-free phone (Table 1). The other half of the participants drove without completing the secondary task. The mental arithmetic task consisted of simple multiplication questions (times tables) presented aurally at a comfortable pace by an off-site experimenter, with each new problem following the participant's previous answer. The problems began at the start of the first lap and ended upon completion of the third lap.

Table 1. Participant demographics.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Secondary Task ($n = 8$)</th>
<th>Driving Only ($n = 8$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Female</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Mean age (years)</td>
<td>44.3</td>
<td>43.4</td>
</tr>
<tr>
<td>Age range (years)</td>
<td>21-61</td>
<td>28-59</td>
</tr>
</tbody>
</table>

Braking Event

The braking scenario was intended to simulate a lead vehicle braking event. The test vehicle followed a lead vehicle towing a trailer with a balloon car on it (Figure 3). At a pre-specified point in the drive (see vehicle icons on Figure 2), unknown to drivers, the lead vehicle released the balloon car off the back of the trailer directly in front of the test vehicle. Experimenters maintained that the event was unintentional until debriefing.

Data Reduction

Data from pilot participants were removed from these analyses. The data from 16 remaining participants (8 females; mean age females: 41.9 years old; mean age males: 45.8 years old) were evaluated.

Acquisition of Reaction Times

Driver reaction times are typically measured from the time that an emergency situation begins (i.e., a lead vehicle braking event or path incursion) to the time that a driver touches the brake [32, 33, 34, 35]. To determine drivers' reaction times to the release of the inflatable target vehicle, the video recordings of the target vehicle deployment (from the windshield camera) and the driver's foot movements (from the footwell camera) were analyzed by two independent raters. Specifically, the raters determined: 1) the first time point at which the target vehicle (i.e., balloon car) could first be perceived to move backwards from the trailer, and 2) the first time point at which the driver's foot touched the brake pedal. The difference between these two time points was defined as the driver's reaction time. Inter-rater reliability was very high, with a significant positive correlation for both the target vehicle deployment times ($r = .99, p < .001$) and foot movement times ($r = .99, p < .001$).

Data Synchronization

Data from the videos, the vehicle's CAN recorder and the high-precision GPS system were synchronized based on a signal flash visible in the video camera recordings and signified by a change in polarity in a specific channel of the CAN recorder. The timing of the vehicle deployment and of participants' responses, as ascertained from the videos, was added to the point of change in polarity to estimate the timing of the balloon car release and participant braking and steering responses in the CAN data.

Data Analysis

Independent-samples t-tests were used to examine differences among males and females, age groups, and secondary task. Descriptive statistics reported include the median as the measure of central tendency to account for the expected positive skew of reaction times.

Results

FCWM Activation

Overall, participants successfully avoided colliding with the inflatable target vehicle. Specifically, 14 of the 16 participants were able to avoid striking the inflatable target without intervention from the autonomous braking system, and 12 of those 14 participants were able to respond either before or without collision warning activation.

As seen in Figure 4, the collision warning system activated for 11 of the 16 participants. Of these 11 participants, seven braked before the audiovisual collision warning activated, and four braked after the collision warning. Both the collision warning system and autonomous braking activated for the two participants who ultimately struck the target vehicle (Participants 11 and 12). These two participants also began to respond prior to the collision warning. These results are summarized in Figure 4. Examination of the video footage suggests that the two participants who collided with the lead vehicle possibly through a combination of short stopping distance and the balloon car's rearward momentum following its release; and that they collided at low speeds, consistent with the intent to mitigate a forward collision.
Reaction Times
Nearly all participants responded quickly to the release of the target vehicle, with a median reaction time of 284 ms. Although the reaction times were numerically faster for males (median = 217 ms) than for females (median = 306 ms), this difference was not statistically significant (p = 0.60). Similarly, when we grouped participants by age to compare younger (younger than 45, mean age = 31.6 years) and older adults (45 and older, mean age = 53.3 years), we found that although the reaction times of younger adults (median = 312 ms) were numerically slower than those of older adults (median = 234 ms), this difference also was not statistically significant (p = 0.35).

Reaction Time and FCWM Activation
The seven participants who responded prior to the audiovisual collision warning reacted approximately 230 ms after the balloon vehicle released and approximately 478 ms prior to the collision warning, on average. The four participants who responded after the audiovisual collision warning reacted approximately 330 ms after the balloon vehicle released and approximately 304 ms after the audiovisual collision warning activated, on average. It should be noted that for two of these participants, the collision warning activated prior to (approximately 4 ms and 760 ms, respectively, before) the balloon vehicle release; and for one participant, the collision warning activated simultaneously with balloon vehicle release, owing to the participant following the lead vehicle too closely.

Participants 11 and 12, for whom the autonomous emergency braking activated, began to react approximately 573 ms before the collision warning activated. Based on the video recordings of the dashboard, the autonomous braking activated approximately 3.49 seconds and 4.50 seconds, respectively, after each respective driver began to react (Figure 5).

Effects of Secondary Task
The secondary task was found to have an effect on participants' driving performance. Although the collision warning system activated with approximately equal frequency both with and without the secondary task, it was found that of the seven participants who braked before the activation of the warning system, five were in the driving only condition (Figure 6). Furthermore, three of the four participants who responded following the collision warning were performing the secondary task.

Additionally, an independent samples t-test on the reaction times revealed a significant effect of the secondary task, such that reaction times in the secondary condition (median = 350 ms) were slower than those in the driving only condition (median = 208 ms), t(14) = 1.81, p < .05.

Figure 4. Participant interactions with FCWM.

Figure 5. Event timeline for participants who activated autonomous braking.

Figure 6. Effects of secondary task on FCWM utilization.
The effects of the secondary task on responses were modified by the presence of the collision warning. Participants who reacted before the collision warning did so approximately 680 ms after balloon car deployment when performing the secondary task, compared to approximately 180 ms after deployment when driving only. By contrast, participants who reacted after the collision warning did so approximately 370 ms after balloon car deployment when performing the secondary task, compared to approximately 200 ms after deployment when driving only. Thus, the collision warning improved responses when performing the secondary task by approximately 310 ms, when compared to responses made before the collision warning.

**Autonomous Braking**

Because Participants 11 and 12 appeared to react in an appropriate time, we examined their responses in further detail to attempt to determine if some aspect of their responses contributed to the activation of autonomous braking. We found that they were not driving faster than other participants: they were driving at approximately 35 and 37 mph, respectively, at the time of balloon car deployment, whereas the other participants were driving between 34 and 43 mph. They were also not driving more closely to the lead vehicle than other participants, based on both an inspection of the in-vehicle videos as well as the fact that the audiovisual collision warning did not activate prior to the balloon car deployment.

Another possible reason that the autonomous braking engaged for Participants 11 and 12 may be that they used insufficient brake pedal force. Examination of the maximum brake pedal loading between the release of the balloon car and the time that the vehicle came to a stop indicated that the maximum brake pedal force used by the other nine participants who received the collision warning but did not experience autonomous braking (median = 21.18 lbf) was greater than the force used by Participants 11 and 12 (19.11 and 18.88 lbf, respectively); however, that force was not the lowest maximum force value of the 11 participants who received the collision warning (14.12 lbf).

**Discussion**

The present study was undertaken to evaluate the effects of FCWM and autonomous emergency braking on driver behavior and response in an emergency situation (i.e., an unexpected lead vehicle braking event); specifically, we examined system actuation and its effects on safety with and without simultaneous secondary task performance. When drivers in our study triggered the FCWM system, it primarily served as a warning to help them respond appropriately to the emergency situation, particularly when performing a secondary task while driving. The autonomous braking system activated for only two participants who also received the audiovisual collision warning but appeared not to respond adequately to avoid autonomous vehicle intervention.

The data revealed a couple of interesting outcomes. These data show that the most important system in a vehicle is a reasonably alert and attentive driver. This conclusion is supported by the fact that more than half the participants began to respond to the presence of the impending collision with the rapidly decelerating balloon car prior to the forward collision warning systems activating (or responded with sufficient speed to avoid the collision warning entirely); and all but two participants were able to successfully avoid colliding with the lead vehicle without autonomous emergency braking. Similarly, although the system did assist drivers engaged in the secondary task, the task elicited performance decrements in the form of delayed responses relative to those participants who were not engaged in the cognitive secondary task.

Consistent with existing literature, we found that engagement in a cognitive secondary task (i.e., mental arithmetic on a hands-free cell phone) decreased a driver's ability to anticipate and react to the lead vehicle braking; fewer participants were able to respond prior to the collision warning when performing the secondary task than when not, indicating distraction effects. However, the collision warning did provide a safety benefit to those drivers engaged in the secondary task as they were still able to react effectively to the lead vehicle and avoid the collision following the collision warning. Participants performing the secondary task were able to respond more than 300 ms faster when alerted by the collision warning than participants performing the secondary task who were not alerted. Thus, although the cognitive distraction introduced by the secondary task may have taken participants “out-of-the-loop” [26], the audiovisual collision warning helped to bring the driver back into the loop so that he or she could react safely. Previous research suggests that ADAS which support drivers and force them to maintain situational awareness are preferable to ensure that drivers maintain their ability to respond quickly [19, 27, 28]. However, numerous studies indicate that drivers utilizing ADAS prefer to engage in secondary tasks [20], suggesting that the lure of distracting in-vehicle tasks may become more appealing as the vehicle becomes more self-sufficient and it may be more difficult for drivers to remain attentive to the road. The present results indicate that warning systems may be able to moderate the difference between drivers' desire to stay engaged in the driving task versus engaging in other activities, such as looking at their cell phone, by using warnings to facilitate drivers' abilities to re-engage in the driving task following prior disengagement.
We considered several potential reasons that autonomous braking activated for two participants, compared to the other 14 participants for whom autonomous braking did not activate. We did not find that these two drivers engaged in risky driving behaviors, such as increased speeds and decreased headway, when driving with FCWM, contrary to previous research \cite{7, 12, 22}. Rather, we observed that even those participants for whom autonomous braking engaged drove at or near the speed limit of 35 mph. Further, these drivers did not follow the target vehicle any more closely than other drivers did, as evidenced by the lack of collision warnings prior to the balloon vehicle's release. These two drivers also responded to the balloon vehicle before the collision warnings activated, suggesting that they were attentive to the emergency situation ahead. Finally, the force they used to carry out their braking response was equivalent to that of other participants. Taken together, we believe these two participants must not have responded sufficiently in some way and thus experienced the autonomous braking, but the nature of the insufficiency is not immediately apparent based on our data. Other possibilities that we have not yet explored include the relative positions of the FCWM-equipped vehicle and the balloon vehicle, which varied somewhat around the target headway over the course of the drive; the time to reach maximum brake pedal force following the balloon vehicle's release; and the specific release path of the balloon vehicle (see below).

It is important to note that the autonomous braking system did not successfully prevent a collision in these two cases of autonomous braking in the present study, even though we note that both collisions were at much lower speeds than the vehicle was initially traveling. Observation of the video footage indicates that the collisions were possibly related to the balloon car's tendency to bounce backward following its release. Thus, we cannot say whether the autonomous braking system would have successfully avoided a collision in these situations because of the balloon car's movement as the following vehicle came to a stop. However, testing the mechanics and effectiveness of the system was beyond the scope of the present study. Our interest was in the naïve driver's response to collision warnings and autonomous vehicle braking in an emergency situation.

Following Parasuraman et al.'s stage model of automation \cite{30}, the present results indicate an easily obtained safety benefit for automated information acquisition and analysis. The pattern of results supports the implementation of this type of ADAS technology as a driver support system, rather than a driver replacement system. Previous research has shown that such a system of driver support, rather than automation, is currently preferred by drivers \cite{27}. The forward collision warning and mitigation technology used in this experiment is designed to give the driver every opportunity to respond before the autonomous emergency braking system engages. In other words, as the vehicle approaches an impending forward collision the ADAS technology goes through a three stage graded intervention:

1. System does nothing, driver responds
2. System warns the driver with auditory and visual signals, driver responds
3. System warns the driver with auditory and visual signals, driver does not respond, vehicle's auto-braking engages

For example, if a driver is approaching an impending forward collision with his or her foot on the accelerator and does not respond prior to reaching a certain time-to-collision threshold, the forward collision visual and auditory warnings will activate. If the vehicle continues towards the collision point without any driver response and reaches an even shorter time-to-collision threshold, then, and only then, will the auto-braking system come on. If prior to this point the driver inputs either a pedal (i.e., sufficient brake application) or steering input, and the vehicle deems this input as a collision avoidance maneuver, then the auto-braking system will not activate. Thus, the system is designed to defer to the driver.

It is clear from both the pattern of responses observed in this experiment, as well as from the forward collision warning and mitigation system's design of deference to the driver, that the human remains an essential and important system in safe vehicle operation. Until autonomous vehicle and infrastructure technology supports fully autonomous driving, there will always be an important driver-vehicle and driver assistance systems interaction. For as long as these partially autonomous conditions exist, human factors research and investigations are necessary to examine the degree or extent to which the inherent response capabilities of both the vehicle and the ADAS technology are being utilized in everyday and emergency driving situations.

**Future Directions**

The results of this preliminary study suggest several extensions and expansions of these methods which may enhance understanding of driver behavior with autonomous vehicle systems. First, the drivers in the present study exhibited extremely short reaction times. This may be related to several factors, including typically fast response times when following a lead vehicle at short headways. For example, Schweitzer et al. \cite{36} found that drivers following a lead vehicle at 12 meters (approximately 40 feet) responded to a lead vehicle braking event within 721 ms when they were naïve to the event and 655 ms when they were partially aware that the event may occur. Additionally, due to the protection afforded to the study's drivers by the closed course, our participants may have been more focused on the lead vehicle than they would be in an everyday driving situation, leading to faster reactions to otherwise unexpected events. The possibility of heightened driver attention is supported by the lack of alerting effects following the audiovisual collision warning for those participants who were driving only, without a secondary task.

Furthermore, drivers may not have been distracted by the arithmetic task as much as by a real cell phone conversation or other, more intensive cognitive distractions. Similarly, some drivers may have been more distracted by the arithmetic task than they would be by a real cell phone conversation. We are currently planning additional studies to increase the complexity of the task such that drivers must attend to more potential hazards in the roadway than the single lead vehicle, to increase eyes-off-road time to manipulate distraction (consistent with research indicating that this is a more reliable detriment to driving performance than is cognitive distraction; \cite{37, 38}), and to increase driver workload while distracted.

Second, we required drivers to maintain a relatively high speed for a relatively short headway in order to exploit the autonomous emergency braking as much as possible. Given drivers' ability to respond regardless of the manipulation, we are in the process of
assessing alternate technical adjustments to the protocol (e.g., shorter headway at balloon car deployment; directing driver's gaze elsewhere at time of deployment) which may elicit higher rates of autonomous braking system activation. Third, our observation that younger participants reacted more slowly than older participants is at odds with much scientific literature; we expect that this finding is primarily related to low statistical power and could be reversed with the addition of more participants. Furthermore, we did not find age to be associated with differences in driver interactions with FWCM. A more detailed analysis of age groups with a wider sample of drivers is necessary to examine whether driver response and acceptance of ADAS technologies is related to cohort effects. Fourth, driver expectations of their own role in the vehicle may play a large part in their reactions. For example, a driver who is aware of an autonomous braking system may not easily rely on the system if he or she is accustomed to controlling the entirety of the vehicle's braking maneuver. The influence of potential expectations is unknown but can be studied in the future by comparing the performance of drivers experienced with autonomous ADAS to the performance of drivers who are not so experienced. Finally, the prevalence of driver responses prior to the activation of the collision warning may indicate that drivers in fact increased headways to avoid collision warnings, as has been seen in previous work [15]. If this is the case, it supports the suggestion that FCWM acts as a tailgating warning as well as a collision warning, and suggests that the collision warning system activation prior to balloon car deployment for two participants served as such a tailgating warning rather than a false positive to a possible impending collision. Future work is needed to assess this possibility and the potential for habituation to or active ignorance of the collision warning if drivers persist in tailgating.

Summary/Conclusions

These initial findings indicate that the participants responded as one would expect a prudent, attentive driver would in an emergency situation. The FCWM technology did not lead to riskier driver behaviors in the context of our study, nor did it disrupt the driver's ability to control the vehicle. Instead, the technology facilitated the driver's intended behavior even in the presence of cognitive distraction. Thus, when an ADAS technology such as a forward collision warning and mitigation is well-designed, the combination of driver attention, auditory and visual warnings, and autonomous braking will assist drivers in mitigating or completely avoiding many forward collisions that might otherwise happen.

References


