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Drivers anticipate lead-vehicle conflicts during automated longitudinal control: Sensory cues capture driver attention and promote appropriate and timely responses

Alberto Morando[a,*], Trent Victor[a,b], Marco Dozza[a]

[a] CHALMERS – University of Technology, Department of Applied Mechanics, Division of Vehicle Safety, Sweden
[b] Volvo Car Safety Centre – Volvo Car Corporation, Sweden

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ABSTRACT

Adaptive Cruise Control (ACC) has been shown to reduce the exposure to critical situations by maintaining a safe speed and headway. It has also been shown that drivers adapt their visual behavior in response to the driving task demand with ACC, anticipating an impending lead vehicle conflict by directing their eyes to the forward path before a situation becomes critical. The purpose of this paper is to identify the causes related to this anticipatory mechanism, by investigating drivers' visual behavior while driving with ACC when a potential critical situation is encountered, identified as a forward collision warning (FCW) onset (including false positive warnings). This paper discusses how sensory cues capture attention to the forward path in anticipation of the FCW onset. The analysis used the naturalistic database EuroFOT to examine visual behavior with respect to two manually-coded metrics, glance location and glance eccentricity, and then related the findings to vehicle data (such as speed, acceleration, and radar information). Three sensory cues (longitudinal deceleration, looming, and brake lights) were found to be relevant for capturing driver attention and increase glances to the forward path in anticipation of the threat; the deceleration cue seems to be dominant. The results also show that the FCW acts as an effective attention-orienting mechanism when no threat anticipation is present. These findings, relevant to the study of automation, provide additional information about drivers' response to potential lead-vehicle conflicts when longitudinal control is automated. Moreover, these results suggest that sensory cues are important for alerting drivers to an impending critical situation, allowing for a prompt reaction.

1. Introduction

Adaptive cruise control (ACC) is an advanced driver assistance system (ADAS) that automates the longitudinal control of the vehicle. This system, classified as level 1 automation (NHTSA, 2015; SAE, 2014), maintains speed and time headway according to chosen settings. The driver activates and sets the ACC system by pressing buttons on the steering wheel. When a lead vehicle is detected, the speed is automatically controlled to keep the selected headway. However, ACC's braking capacity is limited to a level sufficient for normal headway maintenance situations, not extreme braking situations. The allowed deceleration varies among implementations, but the ACC maximum braking authority is usually about 0.3 g, as suggested in the standards ISO 15622:2010 and ISO 22179:2009. When the driving situation exceeds the braking capacity of the ACC, because of a highly decelerating lead vehicle, for example, a frontal collision warning (FCW) is issued. The FCW's role is to redirect the driver's attention to the forward road and elicit a driver braking response in critical situations, by means of visual and auditory signals. ACC has primarily been seen as a system supporting normal driving situations, for comfort. However, by maintaining a safe speed and headway, ACC and FCW have been shown to improve safety-related measures, reducing the exposure to critical situations (Malta et al., 2011; NHTSA, 2005).

Based on the hierarchical structure proposed by Michon (1985), ACC primarily supports the driver at the *control* level (i.e. accelerating and braking) and the *maneuvering* level (i.e. speed selection, gap acceptance and obstacle avoidance); it does not perform the entire dynamic driving task. The driver must monitor the system and take over when required, either by the system itself (e.g., when a FCW is issued) or when ACC does not react to a lead vehicle due to system limitations, such as the radar's field-of-view. Several studies

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[*] Corresponding author at: SAFER, Box 8077, 402 78 Göteborg, Sweden.
E-mail address: alberto.morando@chalmers.se (A. Morando).

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questioned the ability of a driver to reclaim control in an effective and safe manner after a system failure. They raised concerns about the harmful effect of ACC (and, by extension, of higher levels of automation) due to the degradation of *situation awareness* and a slower response to critical events (for example); for a review see de Winter et al. (2014). Situation awareness is defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley, 1988, p. 792). The review by de Winter et al. (2014) shows that results for situation awareness vary between studies. ACC use can result in deteriorated situation awareness when drivers engage in secondary tasks, but improves situation awareness if they are attending to the driving task. Similarly, a number of experiments have found that ACC drivers can be slower to respond to critical events compared to manual drivers, while many studies have shown faster reactions to artificial visual stimuli (de Winter et al., 2014). A more nuanced examination of the response processes in critical events when using ACC is clearly needed.

A possible explanation for degraded detection of and response to critical driving situations can be regarded as an unintended effect, also known as *behavioral adaptation* (OECD, 1990). For example, ACC decreases the visual demand of driving; as a consequence drivers use freed resources to engage in non-driving activities, which may reduce the attention allocated for monitoring the road ahead (Rudin-Brown and Parker, 2004). The widespread availability of in-vehicle infotainment systems and nomadic devices may further aggravate this effect (Lee et al., 2006). In their naturalistic study, Malta et al. (2011) found a general increase in secondary-task engagement while driving with ACC. A follow-up study by Tivesten et al. (2015) examined the drivers' visual attention in motorway car-following scenarios. In steady state driving, the analysis confirmed a lower attention level to the forward path with ACC than without (~77% mean eyes on path with ACC, compared to ~85% for manual driving without ACC). Tivesten et al. (2015) also clarified that most of the glances away from the forward path were driving-related. Because driving relies heavily on vision (Shinar, 2007), diversion of visual attention from the forward road could lead to a collision there. However, Malta et al. (2011) pointed out that drivers kept their attention on the primary driving task in critical situations. Furthermore, Tivesten et al. (2015) showed a *threat anticipation* response: drivers anticipate the impending criticality by directing their eyes to the forward roadway before a situation becomes critical. This is evidence that allocation of attention away from the road is a function of the current driving situation demand (Ranney, 1994; Summala, 2007).

A simulator study by Lee et al. (2006) evaluated the effectiveness of warning modalities at reengaging drivers when the ACC capabilities are exceeded. Their results showed that if warned that an intervention is needed, drivers could effectively resume control even if distracted. However, other studies showed that drivers responded poorly to unexpected events or failures for which alerts are not provided—for example, sensor failures (Nilsson et al., 2013; Rudin-Brown and Parker, 2004; Stanton et al., 1997; Strand et al., 2014). Fortunately, in the real world these failures are rare, thanks to technology advances and sensor redundancy; even so, providing feedback on the system status and availability is recommended by the standard ISO 15622:2010. Therefore, the difficulties encountered by drivers may be overrepresented in studies when such feedback is not provided (Lee et al., 2006).

Although the FCW is intended to redirect the gaze of the driver towards the forward path and inform the driver that an avoidance maneuver is needed, the results in (Tivesten et al., 2015) suggested that there may be other cues that elicit a shift of visual attention in anticipation of a critical situation, even before an FCW is issued. However, the cause for this anticipatory mechanism was not clearly identified; hence the need for further investigation. Tivesten et al. (2015) showed that the average percent of eyes on path increased steadily over time, and they suggested that this increase was due to drivers' reactions to external stimuli (e.g., related to the approach toward the lead vehicle).

This study discusses three sensory cues which are considered relevant for prompting the drivers' visual attention towards the forward path in anticipation of a lead vehicle conflict. The first cue is the detection of the longitudinal acceleration of the driver vehicle by the vestibular system. As pointed out in (Lee et al., 2006, 2007), another benefit of the ACC is that the cue associated with the speed modulation (deceleration or braking) before the onset of the warning may be particularly effective at alerting drivers and making them resume control when needed. Subjective data from a field operational test of ACC (Fancher et al., 1998) indicated that drivers acknowledged the deceleration cue as beneficial for informing them of an evolving headway conflict. Lee et al. (2006) found the detection threshold to be between 0.15–0.20 m/s^2. However, this deceleration cue effect is often discounted in studies in fixed-base simulators, since they do not provide these deceleration cues.

The second cue is visual looming, the optical expansion of the lead vehicle in the eye of the driver. Visual cues have been shown to be particularly relevant in car-following scenarios. Previous studies have argued that the driver could detect changes in relative velocity and control the evasive maneuvers (e.g., braking) based solely on information like the visual angle subtended by the lead vehicle $\left(\theta\right)$, the rate of change $\left(\dot{\theta}\right)$, or the combination thereof (τ) (See, for example, Hoffmann, 1968; Hoffmann and Mortimer, 1994a; Lee, 1976; Mortimer, 1990). More details on these measures are given in Section 2.5. Visual detection performance generally deteriorates towards the retinal periphery, therefore the further the driver diverts the eyes away from the forward path the worse the ability to detect threats and objects on the road (Victor et al., 2008). However, results from laboratory experiments show that certain salient stimuli (e.g., moving and looming targets) induce automatic and reflexive reactions. When one of these stimuli occurs, the attention is shifted to the stimulus, especially when it is not expected (Jonides, 1981; Klein et al., 1992; Regan and Vincent, 1995). The salient stimuli expected to elicit an attention shift are associated with behavioral urgency. For example, given stimuli of the same magnitude, looming objects indicate an impending collision and would trigger a reflexive response, whereas receding objects should not elicit the same response, being neither potentially urgent nor threatening (behavioral urgency hypothesis in Franconeri and Simons, 2003; Lin et al., 2008). In on-road studies, drivers could detect a closing car even when visual attention was diverted away from the road, but with increasing eccentricity the threshold for detection increased (Lamble et al., 1999; Summala et al., 1998). (The table in Appendix B provides a compilation of the results from these two studies.) When looking along the line of motion, the perceptual threshold of $\dot{\theta}$ for discriminating the closure of the lead vehicle was around 0.0036 rad/s (with a minimum value of 0.0022 rad/s), regardless of the test conditions (initial headway, speed, and deceleration). This threshold is higher than, yet comparable to, the value of about 0.0030 rad/s, which was proposed by studies from experiments in which the participants were required to watch film clips, and from reviews of previous findings (Hoffmann and Mortimer, 1994a,b; Mortimer, 1990). With increasing eccentricity, the detection threshold for $\dot{\theta}$ increases linearly. However, there is little agreement on the results for τ^{-1} since, unlike $\dot{\theta}$, this variable may be quite sensitive to the different experimental conditions.

The third cue is the brake light onset. The brake light onset signals that the lead vehicle started braking, but its predictive value is limited and it does not give information about the criticality of the situation, e.g., whether/how hard one must brake (Lee, 1976).