Transportation Research Part F 27 (2014) 196–217

Contents lists available at ScienceDirect

Transportation Research Part F

journal homepage: www.elsevier.com/locate/trf

Effects of adaptive cruise control and highly automated driving on workload and situation awareness: A review of the empirical evidence

Joost C.F. de Winter [a,*], Riender Happee [a], Marieke H. Martens [b,c], Neville A. Stanton [d]

[a] *Department of BioMechanical Engineering, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands*
[b] *Centre for Transport Studies, University of Twente, Drienerlolaan 5, 7522 NB Enschede, The Netherlands*
[c] *TNO Human Factors, Kampweg 5, 3769 DE Soesterberg, The Netherlands*
[d] *Transportation Research Group, Civil, Maritime, Environmental Engineering and Science, Engineering and the Environment, University of Southampton, United Kingdom*

ARTICLE INFO

Article history:
Received 15 October 2013
Received in revised form 9 June 2014
Accepted 26 June 2014
Available online 19 August 2014

Keywords:
Human Factors
Levels of automation
Driving simulator
Meta-analysis
NASA Task Load Index
Secondary task
Distraction
Attention
Eye movements
Psychophysiology

ABSTRACT

Adaptive cruise control (ACC), a driver assistance system that controls longitudinal motion, has been introduced in consumer cars in 1995. A next milestone is highly automated driving (HAD), a system that automates both longitudinal and lateral motion. We investigated the effects of ACC and HAD on drivers' workload and situation awareness through a meta-analysis and narrative review of simulator and on-road studies. Based on a total of 32 studies, the unweighted mean self-reported workload was 43.5% for manual driving, 38.6% for ACC driving, and 22.7% for HAD (0% = minimum, 100 = maximum on the NASA Task Load Index or Rating Scale Mental Effort). Based on 12 studies, the number of tasks completed on an in-vehicle display relative to manual driving (100%) was 112% for ACC and 261% for HAD. Drivers of a highly automated car, and to a lesser extent ACC drivers, are likely to pick up tasks that are unrelated to driving. Both ACC and HAD can result in improved situation awareness compared to manual driving if drivers are motivated or instructed to detect objects in the environment. However, if drivers are engaged in non-driving tasks, situation awareness deteriorates for ACC and HAD compared to manual driving. The results of this review are consistent with the hypothesis that, from a Human Factors perspective, HAD is markedly different from ACC driving, because the driver of a highly automated car has the possibility, for better or worse, to divert attention to secondary tasks, whereas an ACC driver still has to attend to the roadway.

1. Introduction

The idea of fully automated driving is certainly not new. In 1863, Jules Verne envisioned a future Paris featuring driverless trains and carriages propelled by pneumatic and electromagnetic infrastructures (Verne, 1996). In the same period, the Beach Pneumatic Transit Company actually built a driverless wagon transporting passengers through a tunnel beneath Broadway (Beach, 1870). A scale model of an automated highway system was demonstrated at the 1939 New York World's

* Corresponding author.
E-mail address: j.c.f.dewinter@tudelft.nl (J.C.F. de Winter).

http://dx.doi.org/10.1016/j.trf.2014.06.016
1369-8478/

Fair (Fotsch, 2001; Geddes, 1940). Between 1950 and 1990, various researchers in the United States, Europe, and Japan equipped consumer cars with systems that automatically controlled steering and speed (Shladover, 1995). In 1997, demonstrations of automated platooning and lane changing were held on a section of a highway in San Diego (Thorpe, Jochem, & Pomerleau, 1997). Soon after the 1997 demonstrations, the stakeholders of the project agreed that a fully automated highway system was "too much of a 'conceptual leap'" (National Automated Highway System Consortium [NAHSC], 1998, p. 1).

Although many research projects allude to a revolutionary introduction of fully automated driving, the development of automated driving is better described as an evolutionary process. As early as the 1970s, Verplank (1977) stated that this evolution had already been going on for a long time through developments such as spark-advance, choke, automatic transmission, and cruise control, and he predicted that automatic headway and steering control would be introduced in the future. Adaptive cruise control (ACC) can be found in consumer cars since 1995 (Beiker, 2012). ACC is a system that controls longitudinal vehicle motion only and therefore qualifies as *driver assistance* according to the definition proposed by the German Federal Highway Research Institute (BASt) (Gasser & Westhoff, 2012). Note that the Society of Automotive Engineers (SAE) and the National Highway Traffic Safety Administration (NHTSA) have introduced similar definitions of levels of driving automation (see Smith, 2013, for a comparison of definitions).

Developments in stereo cameras, radar, laser, and artificial intelligence have recently given rise to automation that can take over longitudinal and lateral control simultaneously. Some examples are Acura's ACC combined with Lane Keeping Assist (Acura, 2014), BMW's Traffic Jam Assistant (BMW, 2013), General Motor's Super Cruise (Fleming, 2012), Lincoln's Lane-Keeping System with ACC (Lincoln, 2014), Mercedes' Distronic Plus with Steering Assist (Daimler, 2013), Toyota's Automated Highway Driving Assist (Toyota, 2013), and Volvo's ACC with steer assistance (Volvo, 2013). For safety reasons, these systems require the driver to permanently monitor the road and/or intermittently touch the steering wheel (which can be detected by means of a torque sensor; Pohl & Ekmark, 2003). These types of systems qualify as *partial automation* according to the BASt definition. A next step in technological evolution is *highly automated driving* (HAD) where the driver can release the hands from the steering wheel and is no longer required to permanently monitor the road. Note that with HAD the human still has to reclaim manual control occasionally, for example when the functional limitations of the automation are reached. A HAD system provides a warning signal in advance if manual takeover is required.

Until the driving task is wholly automated there will be an appreciable role for the human driver (Alecandri & Moyer, 1992; Barfield & Dingus, 1998; Fenton, 1970; Hancock & Parasuraman, 1992; Sheridan, 1970). Many Human Factors researchers would probably agree that workload and situation awareness are two of the most important Human Factors constructs that are predictive of performance and safety (McCauley & Miller, 1997; Parasuraman, Sheridan, & Wickens, 2008; Sarter & Woods, 1991; Stanton & Young, 2000). Accordingly, the aim of this study is to quantify the effects of ACC and HAD on workload and situation awareness.

Workload and situation awareness are constructs rather than causal agents (Flach, 1995) and therefore require well-defined measurement procedures (Hand, 1996). We define workload as the outcome of questionnaires or tests that assess the cost (Hart & Staveland, 1988) or difficulty (Fuller, 2005) experienced by the driver. HAD and ACC could raise workload with respect to manual driving if the driver has to remain vigilant and monitor the automation status. HAD, and to a lesser extent ACC, could also reduce workload, as the driver is relieved from the cognitive activity associated with manual driving and from the physical activity of moving the pedals and steering wheel. A review study by Dragutinovic, Brookhuis, Hagenzieker, and Marchau (2005) found that in 6 out of 6 driving simulator studies, ACC resulted in lower self-reported workload than manual driving, but quantitative results were not provided. The review of Dragutinovic et al. (2005) requires updating, because a large number of studies have been conducted since and because this review did not include studies on HAD.

We define situation awareness as "knowing what's going on so you can figure out what to do" (Adam, 1993, p. 319). Adam's definition parsimoniously captures the essence of situation awareness, including the classical formulation of Endsley (1988) which states that situation awareness is "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" (p. 97). Concerns have been expressed that HAD (Merat, Jamson, Lai, & Carsten, 2010) and ACC (Carsten, 2004) lead to impoverished situation awareness. Situation awareness can be measured by testing whether the driver has observed and understood the host vehicle's state, the road infrastructure, objects in the environment, and the behaviours of other road users. A well-known technique is SAGAT (Situation Awareness Global Assessment Technique), an approach whereby the simulation is temporarily frozen and the screens blanked. During a simulation freeze, participants fill out a questionnaire sheet probing them about objects and conflicts in the environment. Situation awareness can also be operationalized as the driver's response during a critical event scenario, or it can be inferred from eye-movements.

Using our conceptual driver model in Fig. 1, we hypothesize that HAD induces a major change in workload and situation awareness compared to manual driving or driving with ACC. When using ACC, the control of speed and headway (task 1) is automated, but the driver still closes the lateral loop (task 2). Drivers who steer manually need to visually sample the road and apply steering corrections at least every 3 s (Godthelp, 1984). So when using ACC, there is little opportunity to divert visual attention to non-driving tasks. Directing attention away from the road to competing activities is generally regarded as unsafe, and is more commonly known as "driver distraction" (Ferdinand & Menachemi, 2014; Foley, Young, Angell, & Domeyer, 2013; Green, 1999; National Highway Traffic Safety Administration, 2012; Spiessl & Mangold, 2010).

During HAD, the longitudinal and lateral control loops (tasks 1 and 2) are both automated and it therefore becomes possible to divert attention away from the road and to pick up other tasks, depending on incentives and motivation. If,