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Modeling take-over performance in level 3 conditionally automated vehicles

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ABSTRACT

Taking over vehicle control from a Level 3 conditionally automated vehicle can be a demanding task for a driver. The take-over determines the controllability of automated vehicle functions and thereby also traffic safety. This paper presents models predicting the main take-over performance variables take-over time, minimum time-to-collision, brake application and crash probability. These variables are considered in relation to the situational and driver-related factors time-budget, traffic density, non-driving-related task, repetition, the current lane and driver's age. Regression models were developed using 753 take-over situations recorded in a series of driving simulator experiments. The models were validated with data from five other driving simulator experiments of mostly unrelated authors with another 729 take-over situations. The models accurately captured take-over time, time-to-collision and crash probability, and moderately predicted the brake application. Especially the time-budget, traffic density and the repetition strongly influenced the take-over performance, while the non-driving-related tasks, the lane and drivers' age explained a minor portion of the variance in the take-over performances.

1. Introduction

Automating the driving task brings along various challenges from a Human Factors point of view and has, therefore, become an important research field within the last years. While we currently see Level 2 (SAE J3016 2016) automated vehicles on the road, where the driver is still responsible for the driving task and has to monitor the automation, Level 3 conditional automation is expected to enter mass production within the next few years (Dokic et al., 2015). In Level 3 conditional automation, the driver is required to neither monitor the driving environment nor the automated system performance. As a result of this, the driver may shift attentional resources to other tasks (SAE J3016 2016). Nevertheless, the driver still has to be available for taking over vehicle control in “situations that exceed the operational limits of the automated driving system” (SAE J3016 2016), detected and announced by the automated system. If we assume flawless automated system performance, within its operational limits, the transition from automated driving to manual mode is one of the most important controllability aspects and affects safety of conditionally automated vehicles. This transition from automated to manual driving, referred to as the take-over performance, is key to a successful deployment of Level 3 automation. Additionally, the take-over process is a fundamental factor in considering various design aspects of the human-machine-interface and the automated driving system. It affects validation, approval and influences current legislative processes (Avery, 2017).

A large variety of take-over studies have been conducted within the past years, giving insight into drivers' behavior in take-over situations. Automation effects, known from other domains like overreliance described by Parasuraman and Riley (1997), or mode confusion addressed by Bainbridge (1983), could also apply to the automation of the driving task. Among others, research showed mode confusion and errors (Petermann and Schlag, 2010), delayed responses to critical rear end collision events (Young and Stanton, 2007; Gold et al., 2013; Merat and Jamson, 2009) and impaired driving performance after automated driving (Levitan et al., 1998). These automation effects influence the human performance when taking over vehicle control from the automated driving system.

In this manuscript, the time-budget refers to the time available between the take-over request (TOR) and the system limit, which represents a critical event requiring active driver intervention. The driver has to relocate hands and feet to the driving position, regain situation awareness and execute an adequate response to the system limit (see also Kerschbaum et al., 2015; Zeeb et al., 2015; Gold et al., 2013 for the take-over process). The time-budget was proven to determine drivers' take-over performance (Damböck et al., 2012; Beukel van den and Voort van der, 2013). In an earlier related reported in Gold et al. (2013), drivers intervened after 2.1 s ($SD = 0.41$) with a time-budget of 5 s, while drivers with a 7 s time budget intervened significantly later (2.9 s, $SD = 0.65$). In line with these findings, Eriksson et al. (2015) also found effects of the time budget on the decision making time and information preferences. This becomes apparent especially in uncritical events that do not require an immediate reaction (e.g. Eriksson and

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Stanton, 2017). The traffic density affects task complexity and performance, where high traffic densities lead to delayed responses and reduced take-over quality in situations where a lane change is required to pass an obstacle blocking the driver's current lane (Radlmayr et al., 2014; Gold et al., 2016). Various studies also investigated effects of performing non-driving-related tasks (NDRTs) just before a take-over situation. While some authors found significant, deteriorating effects of the NDRT (Gold et al., 2015; Zeeb et al., 2016), others found minor detrimental (Radlmayr et al., 2014) or even ameliorating effects of NDRTs on the take-over performance (Neubauer et al., 2012). Automating the driving task is likely to reduce workload and lead to underload, which impairs drivers' performance and ability to reclaim control by a shrinkage of attentional resources (Young and Stanton, 1997; Young and Stanton, 2002). This could explain the positive effect of NDRT found by Neubauer et al. (2012). Furthermore, the effects of age on the take-over performance seem to be limited (Petermann-Stock et al., 2013; Körber et al., 2016). Finally, a driver's experience with previous take-over situations is associated with a significantly improved take-over performance (Petermann-Stock et al., 2013).

The above insights have been derived from controlled experiments reported in previous literature. Such experiments can only consider a very limited number of one or two independent variables at a time, while other factors are kept constant. Hence the combined effect of different factors influencing the take-over performance remains to be established.

The current paper combines the knowledge resulting from several take-over experiments and proposes a quantitative approach for modeling the take-over performance in time-critical take-over scenarios of Level 3 conditional automation. Based on six driving simulator experiments including 753 take-over situations, regression models are presented capturing the take-over performance measures Take-Over Time, minimum Time To Collision (TTC), Brake Application and Crash Probability, and these models were validated using 729 take-over situations from 5 additional experiments of different authors.

2. Methods & results

2.1. Design of take-over experiments

A large dataset including different influencing factors is needed in order to model the take-over performance in Level 3 conditional automation. Within the last years, the authors conducted a series of driving simulator experiments with a similar design and using comparable equipment, from which an adequate modeling database has been derived. The experimental procedures are reported in detail in previous publications as summarized in Table 1. The modeling approach is reported in detail in Gold (2016), including additional driver performance metrics and intermediate model versions.

The experiments focused on taking over vehicle control from the automation on three-lane highways at a speed of 120 km/h (approx. 75 mph) in critical take-over scenarios. The system limit was represented by two crashed vehicles blocking the current lane. This scenario was selected, as system limits on a highway are most likely to be located ahead and within the current lane of the ego vehicle. The selected scenario is beneficial from a methodical point of view. Situational parameters can be described unambiguously, which facilitates the assessment of driver's performance and supports replicability of the take-over experiment. To impose an exact time-budget, the situations either suddenly appeared at a certain distance or were masked by a vehicle driving ahead of the ego vehicle that changed lanes right before the accident (thereby concealing the system limit). In order to demand a driver response, there was no automation induced minimal risk maneuver implemented. The TOR was presented as an audio-visual warning signal. Experiments were conducted in rather high fidelity driving simulators (fixed based or dynamic) with full vehicle mockups, a field of view of more than 200 ° and a representation of all driving mirrors.

2.2. Independent variables

Six independent variables were varied within the experiments.

- The **Time Budget (TB)** is defined as the time between the TOR and the system limit. The TB determines the driver's reaction in the take-over situation by creating time pressure and thereby affecting performance.
- The **Traffic Density (TD)** within a take-over scenario influences the driver's reaction, by restricting the opportunities for action and prolonging perceptual as well as decision processes due to a higher number of relevant objects.
- The **Lane**. In a similar way, the initial lane (right, center, left) affects the number of maneuvers possible and thereby affects complexity of the situation.
- The **Non-Driving Related Task (NDRT).** As drivers in Level 3 conditional automated vehicles will be allowed to shift attention towards tasks other than driving, several NDRTs have been tested regarding their influence on the take-over performance (see section 2.3). The Surrogate Reference Task (SuRT) (ISO/TS 14198, 2012) and a task with a fill-in-the-blank text (Text) were visually distracting, while drivers were able to observe the road with the NDRTs 20 Question Task (20Q), Manual Task (MT) and in the condition

Table 1
Overview of independent variables.

	No. of Partic.	Time Budget					Traffic Density				NDRT						Repetition	Lane			Age
		5	5.5	6.1	7	7.8	0	10	20	30	None	20 Q*	SuRT	2-Back		MT**		Right	Center	Left	
Gold et al., 2013	n = 32	**X**			**X**		X						X				n = 1	X			m = 28 SD = 9
Gold et al., 2014	n = 32	**X**	**X**	**X**			**X**			**X**			X				n = 4	X	X	X	m = 32 SD = 9
Radlmayr et al., 2014	n = 32				X		**X**			**X**			**X**	**X**			n = 4	X	X	X	m = 34 SD = 9
Gold et al., 2015	n = 24					X	X						**X**	**X**	**X**	**X**	**n = 12**		X		m = 28 SD = 7
Gold et al., 2016	n = 72				X		**X**	**X**	**X**		**X**	**X**					n = 3	X	X	X	**m = 23 SD = 3**
Körber et al., 2016																					**m = 67 SD = 5**

Variables under investigation in the study are given in bold letters.
* 20 Questions Task.
** Manual Task.