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Modelling decisions of control transitions and target speed regulations in full-range Adaptive Cruise Control based on Risk Allostasis Theory

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A B S T R A C T

Adaptive Cruise Control (ACC) and automated vehicles can contribute to reduce traffic congestion and accidents. Recently, an on-road study has shown that drivers may prefer to deactivate full-range ACC when closing in on a slower leader and to overrule it by pressing the gas pedal a few seconds after the activation of the system. Notwithstanding the influence of these control transitions on driver behaviour, a theoretical framework explaining driver decisions to transfer control and to regulate the target speed in full-range ACC is currently missing.

This research develops a modelling framework describing the underlying decision-making process of drivers with full-range ACC at an operational level, grounded on Risk Allostasis Theory (RAT). Based on this theory, a driver will choose to resume manual control or to regulate the ACC target speed if its perceived level of risk feeling and task difficulty falls outside the range considered acceptable to maintain the system active. The feeling of risk and task difficulty evaluation is formulated as a generalized ordered probit model with random thresholds, which vary between drivers and within drivers over time. The ACC system state choices are formulated as logit models and the ACC target speed regulations as regression models, in which correlations between system state choices and target speed regulations are captured explicitly. This continuous-discrete choice model framework is able to address interdependencies across drivers' decisions in terms of causality, unobserved driver characteristics, and state dependency, and to capture inconsistencies in drivers' decision making that might be caused by human factors.

The model was estimated using a dataset collected in an on-road experiment with full-range ACC. The results reveal that driver decisions to resume manual control and to regulate the target speed in full-range ACC can be interpreted based on the RAT. The model can be used to forecast driver response to a driving assistance system that adapts its settings to prevent control transitions while guaranteeing safety and comfort. The model can also be implemented into a microscopic traffic flow simulation to evaluate the impact of ACC on traffic flow efficiency and safety accounting for control transitions and target speed regulations.

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1. Introduction

Automated vehicles are expected to mitigate traffic congestion and accidents (European Commission, 2017). Automated vehicles may have a beneficial impact on road capacity, traffic flow stability, and queue discharge rates (Hoogendoorn et al., 2014). The first step towards predicting these impacts is to investigate currently available systems such as Adaptive Cruise Control (ACC). ACC assists drivers in maintaining a target speed and time headway and therefore has a direct adaptation effect on the longitudinal control task (Martens and Jenssen, 2012). The influence of ACC systems on driver behaviour has been investigated, mainly via driving simulator studies, since the 1990s. On-road experiments (Alkim et al., 2007; Malta et al., 2012; NHTSA, 2005; Schakel et al., 2017) have shown that ACC systems influence substantially driver behaviour. When the ACC is active, drivers keep larger time headways (Alkim et al., 2007; Malta et al., 2012; NHTSA, 2005; Schakel et al., 2017), and change lane in advance to anticipate possible interactions with slower vehicles (Alkim et al., 2007). These results, however, might be influenced by the conditions in which the ACC system is activated, such as light-medium traffic, medium-high speeds, and non-critical traffic situations.

In certain traffic conditions, drivers might prefer to disengage the system and resume manual control, or the system disengages because of its operational limitations. These *control transitions* (Lu et al., 2016) between automated and manual driving may influence traffic flow efficiency (Varotto et al., 2015) and safety (Vlakveld et al., 2015). Lu et al. (2016) classified control transitions based on who (automation or driver) initiates the transition and who is in control afterwards: 'Driver Initiates transition, and Driver Controls after' (DIDC), 'Driver Initiates transition, and Automation Controls after' (DIAC), and 'Automation Initiates transition, and Driver Controls after' (AIDC). The situations in which these transitions happen are influenced by the characteristics of the driving assistance system, the drivers themselves, the road, and the traffic flow (Varotto et al., 2014). Field Operational Tests (FOTs) have suggested that drivers initiate DIDC transitions with ACC systems that do not operate at speeds lower than 30 km/h to avoid potentially safety-critical situations (Xiong and Boyle, 2012), to keep a stable speed in medium–dense traffic conditions (Viti et al., 2008), to adapt the speed before changing lane, to create or reduce a gap when other vehicles merge into the lane, and to avoid passing illegally a slower vehicle on the left lane (Pauwelussen and Feenstra, 2010). Recently, ACC systems operating also at low speeds in stop-and-go traffic conditions (*full-range ACC*), therefore overcoming the functional limitations of earlier versions, have been introduced into the market. These ACC systems might be activated and deactivated in different situations, and are more likely to be active in dense traffic conditions. A controlled on-road experiment showed that drivers using full-range ACC initiate DIDC transitions when exiting the freeway, when approaching a moving vehicle, when changing lane, and when a vehicle cuts in or the leader changes lane (Pereira et al., 2015).

ACC might have a positive impact on traffic flow efficiency when it is active in dense traffic (Van Driel and Van Arem, 2010). To evaluate this impact, mathematical models of automated and manually driven vehicles can be implemented into microscopic traffic simulation models. However, most car-following and lane-changing models currently used to evaluate the impact of ACC do not describe control transitions. A few microscopic traffic simulation models (Klunder et al., 2009; Van Arem et al., 1997; Xiao et al., 2017) have proposed deterministic decision rules for transferring control, disregarding inconsistencies in the decision-making process, heterogeneity between and within drivers, and dependencies between different levels of decision making (for a review, we refer to Varotto et al., 2017). Thus, the traffic flow predictions based on these models could be unreliable.

To improve the realism of current traffic flow models, insights from driver psychology and human factors should be incorporated (Hamdar et al., 2015; Saifuzzaman and Zheng, 2014). To date, few studies have proposed a conceptual model framework explaining control transitions based on theories of driver behaviour and have estimated the probability that drivers transfer control based on empirical data. Using a mixed logit model, Xiong and Boyle (2012) predicted the likelihood that drivers would brake resuming manual control while they were closing in on a leader. Recently, we identified the main factors influencing drivers' choice to initiate a DIDC transitions with full-range ACC in a wider range of situations which did not involve lane changes (Varotto et al., 2017). Drivers have higher probabilities to deactivate the ACC when closing in on a slower leader, when supposing vehicles cutting in, and before exiting the freeway. Drivers have higher probabilities to overrule the ACC system by pressing the gas pedal when the vehicle decelerates and a few seconds after the activation of the system. Interestingly, some drivers have higher probabilities to resume manual control than others. However, this study did not capture explicitly the unobservable constructs that inform driver decisions and ignored the possibility of adapting the ACC system settings (speed and time headway) to regulate the longitudinal control task.

This study develops such a mathematical framework to model driver decisions to resume manual control and to regulate the target speed in full-range ACC. The model is based on the Risk Allostasis Theory (RAT) (Fuller, 2011), captures explicitly interdependencies between the two decisions, and can be fully estimated based on driver behaviour data. The paper is organised as follows. Section 2 reviews driver control theories and driver behaviour models that are suitable to explain driver interaction with ACC. This section concludes with the identified research gaps. Section 3 proposes the con-

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