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Carrot and stick: A game-theoretic approach to motivate cooperative driving through social interaction

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ABSTRACT

This driving-simulator study aimed to motivate cooperative lane-change maneuvers in automated freeway driving under human supervision. Two interaction concepts were designed based on game theory. These concepts supported drivers' cooperation by applying both rewards and sanctions as the proverbial carrot and stick. The *social-status* interaction rewards gap creation by revealing a driver's prior cooperative behavior to other road users. The *trade-off* interaction introduces a system in which points compensate time loss and gain. Both concepts were evaluated from the left- and right-lane perspective, framing 39 participants to "be fast." Drivers in the right lane asked those in the left lane to open a gap to overtake, mediated through a vehicle-to-vehicle connection and an augmented-reality user interface.

Only 67% of the merging requests were accepted by left-lane drivers due to time pressure in the baseline condition. The social-status interaction enhanced acceptance to 86% on average and even to 97% for requests made by drivers marked as cooperative. The trade-off interaction enhanced acceptance to 87% as drivers gained a virtual benefit for losing one second. The subjective evaluation was positive for all conditions, and the social concepts were rated significantly higher on items associated with social relationships. Both social interaction concepts motivate cooperation and shape drivers' behavior even under time pressure. Social mechanisms power maneuver-based local cooperation between traffic participants.

It is expected that involving drivers in cooperative maneuvers has a beneficial effect on traffic performance, which microscopic traffic flow modeling should validate next. Gamified interaction and interface elements involve drivers of automated vehicles into strategic decisions and could help to mitigate automation effects. Since they don't "drive" any more, cooperative interaction concepts now make them "play driving" and formulate pleasing strategies.

1. Introduction

Road vehicles see increasing levels of automation and communication, aiming to enhance safety and traffic efficiency. Near-term automated vehicles will still have a steering wheel and pedals, with a driver expected to resume control in conditions not covered by

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the automation (SAEInternational, 2016). Drivers may also adopt a cooperative role sharing the driving task with the automation (Hoc et al., 2009).

This driving simulator study aims to motivate cooperative lane-change maneuvers under human supervision. To enhance drivers' willingness to open gaps for slower vehicles under time pressure, we draft two game-theoretic, social interaction concepts. These establish rewards and sanctions as the proverbial "carrot and stick."

1.1. The boon and bane of lane changes

We investigate lane changes as a relevant example of cooperative interaction. More than 20% of US freeway fatalities result from weaving crashes (1192 situations were analyzed in Golob and Recker, 2004), which are almost completely attributable to lane changes (Pande and Abdel-Aty, 2006). As safety critical maneuvers, they are *frequent and complex* (Ammoun et al., 2007; Heesen et al., 2012).

Human recognition errors (41–56%) and decision errors (29–52%) are the main causes for such accidents (Treat et al., 1979). However, the merging driver's recognition failures predominate in case of lane changes (comprising 75%, Knipling, 1993). Half of the lane changes observed at the end of an on-ramp are forced (Choudhury et al., 2007). Blind spot *warning* systems can prevent collisions with vehicles that are already passing (Kyriakidis et al., 2015) and could reduce annual vehicle crashes by 7% (Jermakian, 2011).

In this paper, we focus on the timely interaction with vehicles approaching from larger distances. A passing vehicle will need an average time budget of 8–14 s to properly anticipate (Zheng et al., 2013) and react to another vehicle entering its lane (Heesen et al., 2012).

Lane changes are the main reason for the capacity reduction of roads, since their impact on following vehicles causes upstream oscillations (Zheng et al., 2013; Ahn and Cassidy, 2007). Hence, coordination of lane-change maneuvers should optimize *traffic performance and flow* for automated as well as for connected vehicles (Wang et al., 2015).

A field test of V2I lane coordination has reduced speeds and increased margins to improve safety (Farah et al., 2012). Cooperative lane-selection strategies have also increased throughput, even with a low 5% proportion of smart vehicles (Moriarty and Langley, 1998).

1.2. Could a cooperative lane-change assistant put things right?

In previous papers, we presented a cooperative lane-change scenario as depicted in Fig. 1, where a driver in the slow (right) freeway lane asks another in the fast (left) lane to open a gap to overtake (Zimmermann and Bengler, 2013; Zimmermann et al., 2014). The vehicles feature high driving automation (according to SAEInternational, 2016), which expects drivers to monitor the road and the user interface only during the lane-change situation. During normal cruising, the automation operates hands free with the driver's eyes off the road. We implemented an additional cooperative shared control (according to Sheridan and Verplank, 1978; Abbink et al., 2012; Flemisch et al., 2014): While the machine is responsible for longitudinal and lateral control, the driver is still able to steer, accelerate or brake at any time without precipitating a takeover.

Interaction is facilitated *on board*, between human and machine, as well as from the *traffic* perspective, between the two vehicles V_L and V_R. Vehicle V_R ($v = 33$ m/s) approaches a slower obstacle, O ($v = 22$ m/s), and needs to overtake to maintain its speed. Vehicle V_L ($v = 36$ m/s) travels in the dense fast track and is considered an ideal cooperation partner. Its driver is asked to open a gap for V_R. If he or she accepts cooperation, V_L opens a gap. V_R's lane-change decision is driver-initiated (Banks and Stanton, 2016) but automatically completed.

We therefore modeled a *multimodal interaction concept for cooperative driving* within the scope of European research project D3CoS. The cooperative-interaction assistant, hereinafter referenced to as cooperative lane-change assistant (cLCA), first plans, establishes, and manages cooperation with other vehicles (through V2V communication). It then uses an augmented-reality user interface to present cooperation status and action suggestions (Zimmermann and Bengler, 2013). These visual elements, carpets and arrows, support drivers in their decision-making process (Eriksson et al., in press). The interaction concept, which we also use for the study at hand, features the "mutual control" mode of cooperation according to Hoc et al. (2009).

1.3. Motivating cooperation under time pressure, or the aim of the study

The cooperative lane-change assistant demonstrated a striking improvement of left lane drivers' *ability* to cooperate: 36% of the drivers had cooperated without and 88% with the cooperative system (Zimmermann et al., 2014). However, this previous experiment

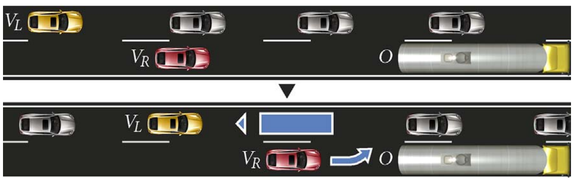

Fig. 1. The lane-change scenario allows a vehicle in the right lane (V_R) to enter a gap (rectangle), which is cooperatively prepared by another traffic participant in the left lane (V_L), before the former rear-ends a slower truck (O).