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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

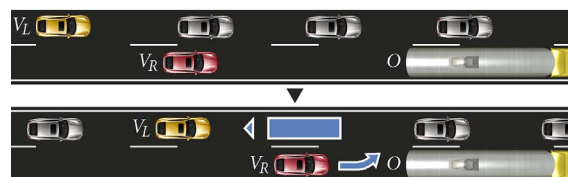


Fig. 1. The lane-change scenario allows a vehicle in the right lane ( $V_R$ ) to enter a gap (rectangle), which is cooperatively prepared by another traffic participant in the left lane ( $V_L$ ), before the former rear-ends a slower truck ( $O$ ).

supposed the need for motivational strategies, since its setting did not affect drivers' willingness to cooperate. While it has been reported that cooperation is intrinsically motivating (Tauer and Harackiewicz, 2004), we know from our daily driving experience and from studies (Choudhury et al., 2007; Moriarty and Langley, 1998) that drivers can also behave uncooperatively. According to Wilde (1976), social habits, values, communication, and expectations affect cooperation as do individual *modulating factors* such as personality tending toward selfish or altruistic, or *motivational states* such as momentary criticality or short-term time pressure.

In this study, we endeavored to analyze and improve willingness to cooperate. Eriksson et al. (2015) have shown *time pressure's* effect on information preferences and decision-making time. We expected time pressure to be the most likely factor exerting a (prototypical and strong) negative impact on cooperative behavior. First, we wanted to show a collapse of cooperation induced by time pressure in our lane-change scenario. Second, we intended to restore cooperation through technological support of social interaction preceding the lane change.

We will use a game-theoretic model of social interaction (Section 2) to first explore our hypothesis and establish motivational concepts. Based on the model, we will layer the motivational-interaction concepts “social-status” and “trade-off” on top of the cLCA (Section 3). Those will be subsequently tested in a driving-simulator study with participants (Sections 4 and 5).

## 2. Modeling social interaction

To analyze and improve interaction in the lane-change scenario, we modeled it as a non-cooperative game,  $\Gamma$ , described in Appendix A. The right-lane driver,  $V_R$ , issues a merging request. The left-lane driver,  $V_L$ , plays first by answering the request with *accept* or *reject*.  $V_R$  can then choose to *change* lanes or to *stay* in the lane resulting in a sequential perfect information game.

As drivers will (most likely) never meet again, it's also a one-shot game. The modeled payoff for both drivers relies on the subjectively perceived value of cooperation (*spvc*, from Zimmermann et al., 2015), a safety factor for when a driver tries to change lane without an existing gap, and the driver's time pressure combined with a time loss of  $-1$  s for  $V_L$  and a gain of  $11$ – $17$  s for  $V_R$ . The objective values are calculated relative to a non-cooperative situation in which they equal 0 s.

We assume time gain, loss, and pressure as predominant measures of efficiency in our model, but these are interchangeable with, for instance, comfort, time, space, velocity, or safety (as modeled in Wang et al., 2015, Eq. (10); Altendorf and Flemisch, 2014, Eq. (9)). As both the signs and the ordinal ranks are the same, opening a gap is a loss for  $V_L$ ; changing lane is a gain for  $V_R$ .

The model identifies the status quo in the previous experiments without time pressure. The cooperative strategy profile (*accept*, *change*) is the rational choice under the premise “be cooperative.” The subjectively perceived value of cooperation dominates, resulting in a Nash (1950) equilibrium for the cooperative strategy—neither driver can increase individual payoff by unilaterally deviating from his or her choice. This is the game's only solution and it's what we observed in our previous experiments (Zimmermann et al., 2014, 2015): left-lane drivers cooperated by opening gaps (88%).

### 2.1. The first problem with lane changes: rational behavior under time pressure

When drivers are framed to “be fast,” we expect time pressure to dominate the subjectively perceived value of cooperation.  $V_L$ 's rational decision to maximize individual payoff by not losing time will lead to uncooperative behavior.  $V_L$  decides the game and thus shifts the Nash equilibrium to the strategy profile (*reject*, *stay*). The model predicts a drop in acceptance rates under our experiment's baseline condition:

**Time pressure restrains cooperation (H1).** Left-lane drivers will behave rationally to maximize their individual progress. The acceptance rate in our baseline (B) will decline under time pressure from the 88% in Zimmermann et al. (2014).

As perceived time pressure varies throughout the trial and conflicts of interest between subjectively perceived value and time pressure arise, participants will implement mixed strategies in left-lane situations when acting as  $V_L$ . That  $V_R$  drivers don't have that conflict (positive value is timely advance) explains why the right-lane success rate was 100% (in Zimmermann et al., 2014) and why our cLCA invariably requests cooperation.

### 2.2. The second problem with lane changes: a social dilemma

These rational—mainly egocentric—decisions will limit both the individual and overall traffic system performance. A joint cost function, “representing the collective situation of all vehicles” (Wang et al., 2015, p. 78) would optimize connected vehicles' performance.

In our scenario, the cooperative play (*accept*, *change*) would lead to an exemplary collective joint optimum of a decent joint subjective perception (*spvc* = 1.5) and a positive joint time gain (*time* = 5 s). The rational (*reject*, *stay*) play would perform comparably worse, with a negative joint subjective perception (*spvc* =  $-0.5$ ) and no joint time gain (*time* = 0 s).

As humans are involved in the decision-making process, we expect them to act rationally as individuals. Moreover, drivers will play the game in the roles of  $V_L$  and  $V_R$  in turn. The individual expected total game utility of a sequence of rational plays (*reject*, *stay*) is therefore also lower than (*accept*, *change*) would be.

This will produce a *social dilemma* with the following horns: “(1) each person has an individually rational choice that, when made by all members of the group, (2) provides a poorer outcome than that which the members would have received if no member made the rational choice” (Messick and Brewer, 1983, p. 15). Drivers will rationally choose to reject cooperation in the left lane under time

pressure. Consequently, the *overall individual* outcome will be worse, due to the repeated plays from the right-lane perspective. Also the *global traffic system*, the joint performance, will suffer from the worse outcome. This renders the rational selfish play (*reject, stay*) suboptimal. In not choosing the preferable (*accept, change*) lies the social dilemma, calling for cooperative systems optimising the collective benefits.

### 2.3. Reciprocity mitigates negative effects

Rational behavior induced by time pressure and the social dilemma, could cause acceptance rates to drop to 0% over time—culminating in no left-lane cooperation at all. Similar effects have been observed in numerous public goods experiments, also exhibiting social dilemmas (Messick and Brewer, 1983; Fehr et al., 2002; Kollock, 1998). However, we don't expect such a drastic decrease, because it would emerge over the course of time rather than instantaneously, by virtue of time pressure's not being constant throughout the experiment, and due to the concept of human reciprocal altruism. The latter is governed by the “criterion of small cost to the giver and great benefit to the taker” (Trivers, 1971, p. 45), which could apply given our left-lane cost of  $-1$  s and right-lane benefit of at least 11 s.

Reciprocity means, that humans behave cooperatively in cooperative environments and uncooperatively in uncooperative ones. It comes, amongst others, in two flavors: direct and indirect. While direct reciprocity (“I help you and you help me”) requires repeated encounters between the same two persons, indirect reciprocity (“I help you and somebody else helps me”) represents a relation between altruistic groups and individuals (Nowak and Roch, 2007, p. 605). We expect the latter to happen on streets. Consequently, indirect reciprocity forms the second hypothesis of our experiment:

**Group behavior mediates indirect reciprocity (H2.1).** The environment will shape drivers' behavior. Drivers are more willing to cooperate in altruistic environments (where other vehicles accept cooperation with a probability of  $2/3$ ), than in egoistic ones (where  $1/3$  of the responses are positive).

Messick and Brewer (1983) and Kollock (1998) summarize several solution strategies for social dilemmas. Communication can facilitate moral suasion and group identity and ultimately compel individuals to consider group interest. In situations where players meet only once, information about others' (previous) choices can also induce such *social identity*. We expected direct reciprocity to emerge from revealed *foreign social status* ( $S_F$ ), based on hitherto cooperative behavior:

**Social information promotes direct reciprocity (H2.2).** Visibility of foreign social status, linked to prior cooperativeness in the interaction concept,  $S_F$ , will shape drivers' behavior. Drivers are more willing to cooperate with drivers who have previously cooperated (bearing positive status) than with those who have not (bearing negative status).

### 2.4. Structural changes to motivate cooperative maneuvers

However, reciprocity alone is insufficient to motivate cooperation. A social norm needs to establish itself between drivers, communicated through social cues (Rakotonirainy et al., 2014). This in turn requires a structural rule change.

Hollander and Prashker (2006) reviewed the literature for such “games between travelers.” While most of these games were on the navigation level (such as routing), we set up a game for playing for the lane-change maneuver. We decided to introduce *reward* (the “carrot”) and *sanction* (the “stick”) in guise of two interactive game concepts.

The idea of the first concept is to make both the *ego* and *foreign social status* ( $S_{E+F}$ ) visible to drivers. Fig. 2 shows this  $S_{E+F}$  game: the strategy of  $V_L$ 's driver influences his or her own status as an additional utility. Accepting cooperation increments this status ( $status + 1$ ), rejecting decrements it ( $status - 1$ ). We limited this  $status \in \{-1, 0, 1\}$  to carry at most two prior decisions.

As right-lane requests neither incur cost nor influence  $V_R$ 's utility, the cLCA invariably requests cooperation in  $S_{E+F}$ . We expect this mechanism to have a motivational effect on  $V_L$ . Mediated through delayed direct reciprocity, the individual outcome will improve. The stigma of noncooperation in the left lane provokes a tit-for-tat response in the right lane later on; distinguishing oneself as cooperative similarly maximizes future utility. This will establish social control in directly reciprocal driving environments. Unlike those in  $S_F$ , simulated cars in  $S_{E+F}$  will respond directly reciprocal.

**Revealed social status promotes cooperation (H3).** The *social-status* interaction concept,  $S_{E+F}$ , will motivate left-lane cooperation, because other drivers will exert social control and react with direct reciprocity.

The goal of the second concept, *trade-off* (T), is to establish a trading system between drivers. It allows them to barter *time* for a *points* currency and vice versa. As shown in Fig. 2, the game directly balances points between the two players.  $V_R$ 's driver pays  $-4$  pt to  $-12$  pt for a lane-change but gains 11–17 s (depending on the number of following vehicles; we detail these conditions in Lütteken et al., 2016).

The taker,  $V_L$ 's driver, while sacrificing  $-1$  s through cooperation, gains 3 pt to 9 pt. The feedback, resulting points, and utility are immediate in T, in contrast to  $S_{E+F}$ . As a lane change now incurs cost, the decision to request cooperation is made by  $V_R$ 's driver. We hypothesize that drivers are more likely to accept lane changes when points are invested and thus also to motivate a social quid pro quo:

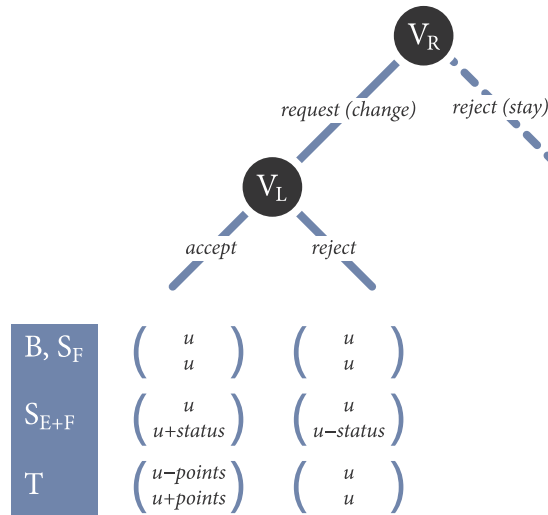


Fig. 2. Extensive form of the structurally modified game. Payoffs are listed as a vector for  $V_R$  (top) and  $V_L$  (bottom) in the baseline (B), foreign-social-status ( $S_F$ ), ego-and-foreign-social-status ( $S_{E+F}$ ), and trade-off (T) interaction concepts. The utility (u) is time, subjectively perceived value of cooperation and safety (from Appendix A), with the structural changes of status or points.

**Trade-off promotes cooperation (H4).** The *trade-off* interaction concept, T, will motivate left-lane cooperation, because points compensate for time loss.

### 3. Interaction design and implementation

To bring social-status and trade-off game concepts to life, we used an iterative user-centered design (UCD) process. We adapted the cooperative lane-change assistant (cLCA) interaction to accommodate our motivational game concepts (building on Zimmermann et al., 2014, 2015).

#### 3.1. User interface elements for the setting

We incorporated time pressure into the user interface; the corresponding elements are shown in Fig. 3. As soon as the driver crosses the racing line, the head-up display indicates the remaining travel distance (D). Knowing the time budget (B), in this example –40 s late, the driver has to implement a cooperative driving strategy to catch up. All seconds gained or lost by cooperation are credited here: opening a gap costs –1 s, changing a lane advances the driver by 11–17 s. The speed is controlled by the automation and displayed by the speed indicator (S). Cooperation is the only rule-compliant way to save time in our scenario. Exceeding the maximum allowed speed or violating safety margins is possible but is immediately avenged by an “annoying” buzzer (which loops while speeding or cutting in, 80 Hz–15 kHz). Such dangerous behavior doesn’t increase the time budget.

The request cluster (Fig. 3, right, top) heralds the request phase to harmonize the interaction across all concepts. Cross and check paddles on the steering wheel are used to accept, request, or reject cooperation (Fig. 3, right, bottom).

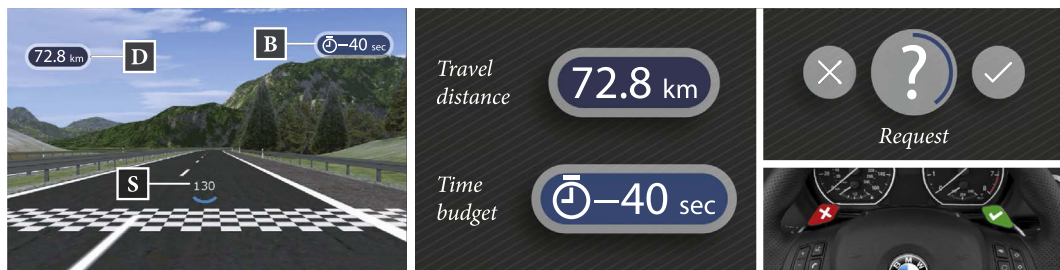


Fig. 3. Left and center: User interface elements for establishing time pressure. Travel distance (D), time budget (B), and a speed indicator (S) extend the static head-up display. Right: cooperative request cluster in the head-up display (top) and steering wheel paddles for answering this request (bottom).



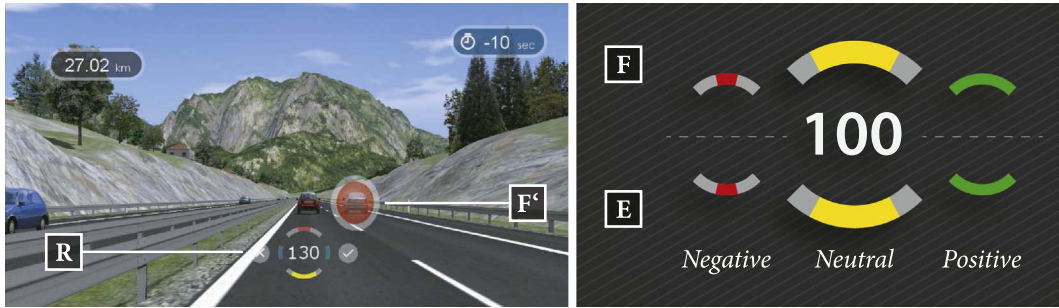


Fig. 4. Visual interface design for the social status interaction concept. Left: yellow (neutral) driver encounters a potential red (previously uncooperative) partner. Right: Detail view of the possible ego (lower arc, E) and foreign (upper arc, F) social states in the driver's static head-up display. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

### 3.2. Social-status interaction concept

The social-status interaction concept categorizes drivers into those with a negative ( $status = -1$ ), neutral ( $status = 0$ ), and positive ( $status = 1$ ) prior behavior. The colors red, yellow, and green mark drivers. Red identifies drivers who have not opened gaps for the last two requests. Green represents drivers who have been cooperative during the most recent two lane changes. We restricted the behavioral memory to those three discrete states and used colors to explore differences in the trade-off concept's points system.

Accepting cooperation in the left lane improves one's own social status (and the associated color) improves by 1. Rejecting cooperation detracts  $-1$  from the status. Having a neutral, yellow status and accepting the request updates one's own status to positive, green after the lane change. Behavior in the right lane does not affect the status.

Fig. 4 shows the visual interface's design, which is based on the cLCA and is arranged around the central speed indicator. The driver's ego status, E, is displayed as a lower arc to establish spatial compatibility. The status of the foreign vehicle is located above the speed indicator; the upper arc, F, points toward the foreign vehicle. The augmented sphere (F') also bears the partner's status. Besides these colors, we used redundant-shape coding (Fig. 4, right): the lower the status, the smaller the shape.

The upper arc of  $V_R$ 's request cluster starts to flash whenever a cooperative request is sent.  $V_L$ 's request cluster (R in Fig. 4) displays the bespoke social-status colors, check and cross icons. Both drivers are informed about the remaining decision time during the 6.3 s long request phase. A closing-circle animation is used as a metaphor to visualize the emerging cooperation of both vehicles. Zimmermann (2016a) and the supplementary video 1 present a video of the social-status interaction concept.

We wanted to investigate the effects of direct reciprocity (H2.2) separate from social status (H3). Based on the social-status concept,  $S_{E+F}$ , we created a new concept featuring less information. The resulting  $S_F$  concept shows only foreign social status (the upper part, F, Fig. 4) without tracking the ego status.

### 3.3. Trade-off interaction concept

In addition to the social-status interaction concept, we designed the trade-off game. The visual interface involves three augmented-reality clusters on the windscreen (Fig. 5) for the lane-change deal. The driver keeps track of the points available for cooperation in the points depot (D) next to the time budget. This cluster is always visible to the driver.

The conditions cluster (C) in the center presents the specific time and point conditions for the cooperation. As soon as the request starts, this cluster fades in and offers individual conditions to  $V_L$ 's and  $V_R$ 's drivers.  $V_L$  loses time through the cooperation and therefore receives points (Fig. 5, left);  $V_R$  is able to gain time through the cooperation and therefore has to pay points (Fig. 5, right).  $V_L$ 's and  $V_R$ 's drivers both have to decide whether or not the conditions offered are worth the lane-change cooperation. The conditions



Fig. 5. Visual interface design for the trade-off interaction concept. Left: the clusters depot (D), request (R), and conditions (C). Right: Detail view of conditions, which were transferred to the depots after a successful lane change.



offered represent the effect of a successful cooperation. Time and point depots remain unaffected if no cooperation is established, because times and points are calculated relative to the non-cooperative situation.

The request cluster (R) in the lower center fades in with an incoming request. The cluster presents the choices to accept or reject cooperation. A circular timer (blue arc) shows the time remaining to answer the request. If both drivers accept, the cooperation is successfully established. R fades out and a check mark fades in. Additionally, C moves up next to D (Fig. 5, right) and waits for the lane-change maneuver. The conditions are passed to the account after the lane change is successfully performed, and a cash box bell rings. If either driver rejects or misses acceptance, cooperation is not established. R fades out and is replaced by a cross to notify both drivers about the noncooperation.

The trade-off system calculates different gainable time and payable points for  $V_R$  depending on the traffic situation. The conditions offered depend on the number of vehicles following behind the left-lane cooperation partner's vehicle,  $V_L$ . The more cars following, the longer  $V_R$  would have to wait before a lane change becomes feasible. The amount of time  $V_R$  stands to gain is the time difference between waiting and cooperating.

The points paid are divided between two recipients.  $V_L$ 's driver receives the lion's share for his willingness to cooperate. Every following vehicle incurring a time loss due to the cooperation also receives a commensurate recompense from  $V_R$ 's driver, who has to pay every left-lane driver directly influenced by his demand for the lane change. We detail the shares in Lütteken et al. (2016).

We used different left-lane densities in this experiment, hence the time/point ratio varied between cheap and expensive. We neglect this factor below; the time/point ratios are detailed and simulated in Lütteken et al. (2016). A video of the trade-off interaction sequence from both  $V_L$  and  $V_R$  perspectives is presented in Zimmermann (2016b) and the supplementary video 2.

## 4. Experimental method

### 4.1. Participants

We set up a driving-simulator study at the Technical University of Munich's Institute of Ergonomics. A sample of 39 persons (8 female and 31 male) between 18 and 56 years of age ( $M = 29$  years,  $SD = 10$  years) participated in the experiment. Their driving experience was 11 years on average ( $SD = 10$  years) with an annual mileage of 9191 km ( $SD = 11,750$  km), 56% drove at least once a week. 31% had prior driving simulator experience. No participant had apparent eyesight or hearing limitations.

### 4.2. Experimental manipulations

We randomized our four interaction concepts as a within-participants factor. A baseline (B) with the cooperative lane-change assistant served to test the effect of time pressure (H1). The foreign-social-status ( $S_F$ ) concept displayed only the partners' social information for exploring direct reciprocity (H2.2). The ego-and-foreign-social-status ( $S_{E+F}$ ) concept added ego social information and was used to test the motivational effect of social status (H3). The trade-off (T) concept served the investigation of its motivational effect (H4) as well. The  $S_F$  concept was always driven before the rule change in  $S_{E+F}$ , since H2.2 was a precondition for H3.

We repeated the lane-change situation 12 times in B,  $S_F$ , and  $S_{E+F}$ , and 18 times in T (which required more repetitions due to the within-participants factor time/point ratio). Participants drove it 6 (or in T 9) times from the left-lane and 6 (or 9) times from the right-lane perspective. The other road users behaved in a programmed manner avoiding accidents in all cases. This led to a total of 54 cooperative encounters per participant. As each situation took 30 s plus approximately the same time both for establishing and clearing the scenario, more repetitions would have been out of scope.

We introduced foreign acceptance of cooperation as a between-groups factor to explore indirect reciprocity (H2.1). Simulated drivers in the left lane cooperated in one third ( $p = 2/6$ ), half ( $p = 3/6$ ), or two thirds ( $p = 4/6$ ) of all requests under the B and  $S_F$  conditions across groups. The simulated vehicles' right-lane social status, negative ( $status = -1$ ), neutral ( $status = 0$ ), and positive ( $status = 1$ ) was equally distributed under  $S_F$  and  $S_{E+F}$  conditions (H2.2).

To investigate social status (H3), simulated foreign left-lane cars' drivers reacted reciprocally based on the participant's ego state across repetitions in the  $S_{E+F}$  concept: They rejected cooperation when encountering a negative driver ( $p = 0$  for  $status = -1$ ), randomized their response for neutral drivers ( $p = .5$  for  $status = 0$ ), and accepted requests of positive drivers ( $p = 1$  for  $status = 1$ ).

In the T concept, simulated partners always accepted requests for cooperation ( $p = 1$ ). We also introduced three different time to point ratios, cheap, medium, and expensive, into the T concept and instructed participants to strive for a high score, which we describe in Lütteken et al. (2016).

As time pressure was an important part of our research design, we kept it as constant as possible throughout concepts B,  $S_F$ ,  $S_{E+F}$ , and T. We instructed participants to "arrive in time" (with a *time budget*  $\geq 0$  s), framed them by a racing line and reminded them by displaying travel distance and time budget (see D and B in Fig. 3), and ultimately offered 50 € vouchers for timely arrival.

### 4.3. Measures

All of our hypotheses rely on cooperative behavior in the left lane. We define the corresponding measure as *acceptance rate*, which is the share of "accept" decisions per request. We define *decision time*, i.e., accepting or rejecting cooperation, from the beginning of the request, heralded by the visual interface cluster (see Fig. 3) and an auditory cue to the driver's decision registered by pressing the "check" or "cross" paddles on the steering wheel. We recorded the *timeliness* (time budget) at the moment of each decision, as well as when finishing the track by crossing the racing line, the *overall timeliness*, and the *points score* in T.

**Table 1**

The concept questionnaire's nine questions based on the transtheoretical model.

Item	Process of change	Question By using the cooperative system, ...
1	Consciousness raising	Did you perceive the lane change LESS/MORE consciously?
2	Dramatic relief	Did you experience the lane change LESS/MORE casually?
3	Environmental reevaluation	Did other road users perceive your (positive or negative) cooperative behavior LESS/MORE intensely?
4	Self-reevaluation	Do you reconsider your own cooperative behavior LESS/MORE?
5	Helping relationships	Did other road users appreciate your cooperative actions LESS/MORE?
6	Self-liberation	Do you drive LESS/MORE cooperatively in road traffic?
7	Social liberation (passive)	Do other road users make you behave LESS/MORE cooperatively?
8	Social liberation (active)	Do you make other road users behave LESS/MORE cooperatively?
9	Stimulus control	Would its discontinuation lead to LESS/MORE cooperation?

To evaluate potential behavioral changes attributable to the different concepts, we developed a *concept questionnaire*. It's based on the psychosocial transtheoretical model (TTM; Prochaska et al., 2008), which conceptualizes the process of intentional behavior change. We designate un-cooperativeness as “bad behavior.”

Our questions target the TTM's cognitive and behavioral processes of change: consciousness raising (supporting cooperation), dramatic relief (negative aspects of cooperation), self-reevaluation (realizing cooperation as important), environmental reevaluation (positive and negative impacts on others), social liberation (realizing social norms change), self-liberation (commitment to change), helping relationships (social support), and stimulus control (adding reminders for cooperation). The questionnaire contains nine questions, as shown in Table 1. All nine items were rated in seven points from 1 (“much less”) to 7 (“much more”) on a Likert-type bipolar scale.

#### 4.4. Experimental procedure

Two out of five experimenters conducted each experiment. To compensate for bias and personal influences, we used checklists and prerecorded voice-over video presentations. The instructor welcomed and introduced participants using a presentation. After they filled out consent forms, a demographic questionnaire, and a behavioral questionnaire, they drove an acclimatization track for approximately five minutes with lane changes and using the cLCA.

The main experimental part consisted of the four randomized concepts B, S<sub>F</sub> and S<sub>E+F</sub>, and T. Each of these was initiated by a briefing voice-over video presentation of about five minutes followed by the recorded track with the corresponding concept employed (about 25–35 min). If the participant arrived in time, an exultant stadium sound was played, otherwise an apologetic one. We told them whether they qualified for the voucher lottery. Participants answered the concept questionnaire after completing each interaction concept.

After those four tracks, the instructor conducted a summative interview concerning the scenario, concepts, interfaces, comparisons, and feedback. Finally, each participant received an allowance of 10 € per hour. Overall, an experiment took three hours.

#### 4.5. Procedure for data analysis

Data was processed by an R script that extracted data for every situation. As our experimental design focuses on the left perspective of the lane-change maneuver (the driver's decision is whether or not to accept a request), we analyzed acceptance rates and decision times for that left-lane perspective (B, S<sub>F</sub>, S<sub>E+F</sub>, T). The right-lane perspective also plays a role in the trade-off (T) concept (whether or not points should be spent for a cooperative request).

Since a simulation track consisted of twelve repetitions (six left, six right; in B, S<sub>F</sub>, S<sub>E+F</sub>) or 18 repetitions respectively (nine from each perspective; in T), we analyzed a total of 1044 situation from the left-lane and 342 in the right-lane perspective (of  $N = 2086$  situations in total). One participant withdrew and had to be excluded in T ( $n = 38$ ). We used Excel to pivot data, and R and SPSS for the statistical evaluation.

We used parametric tests for times, and non-parametric tests for acceptance rates and rated items in the following statistical analyses. For *decision times* we assume an interval scale. Although a Shapiro-Wilk test of normality revealed that the requirement of a normal distribution is not met under the S<sub>F</sub> condition ( $W = .92$ ,  $p = .01$ ), we stick to parametric analyses of variance (ANOVA,  $F$ ) and t-tests ( $t$ ), due to the equal and large sample sizes and interval scale (Glass et al., 1972). We applied median-based non-parametric Wilcoxon signed rank test procedures ( $T$ ) on the ordinal data of the *subjective item ratings* (Jamieson, 2004). Shapiro-Wilk tests furthermore indicated that 33 of 36 group ratings deviate significantly from normal ( $W > .70$ ,  $p < .05$ ).

For *acceptance rates*, we applied only non-parametric tests for two reasons. A Shapiro-Wilk test rejected the normality distribution of acceptance rates under all conditions ( $W > .78$ ,  $p < .05$ ). The resolution of possible proportions was also limited to 1/6 or 1/9 respectively, due to the dichotomous nature of a single decision. This throws the continuous level of measurement of acceptance rates into question and justifies non-parametric tests.

Those were chi-square ( $\chi^2$ ) tests for comparing the decisions between the present and the reference study (Zimmermann et al., 2014), Kruskal-Wallis ( $H$ ) independent-samples tests for comparing between groups, and a Friedman's ANOVA ( $\chi^2_F$ ) and Wilcoxon related-samples signed rank tests ( $T$ ) for comparing within-participants. We controlled the familywise error with sequential Holm-

Bonferroni corrections for both contrasts and post hoc tests (Holm, 1979). We estimated Pearson effect sizes ( $r$ ) from  $z$  standard normal deviates (Rosenthal and DiMatteo, 2001).

## 5. Evaluation results

The response rate of participants in the left lane during the request phase was 97.33% either for an accept (cooperative) or reject (non-cooperative, defecting) decision. In 28 situations, missing responses during requests led to a timeout (also defecting). Given that both partners accepted the cooperation ( $n = 1463$ ), the lane change was successful in 99.31% of all situations. This makes acceptance rates comparable to cooperation rates in Zimmermann et al. (2014).

The cooperation was aborted in ten cases—always by the driver in the right lane. Three attempts failed due to a timeout in the prepare phase and seven because the driver didn't initiate the lane change in time during the suggested action. As the timing model was derived from Zimmermann and Bengler (2013), every cooperation started with the additional request phase 30 s before  $V_R$  reached the obstacle. No crashes occurred, because the automation decelerated when approaching the obstacle.

Differences among the cooperative interaction concepts regarding the acceptance rate are visible in Fig. 6. They differ significantly among the four concepts ( $\chi^2(3) = 37.76, p < .001$ ). Since the omnibus test doesn't target our hypotheses, we used the following a priori contrast analyses.

### 5.1. The effect of time pressure

We previously found a cooperation (i.e., acceptance) rate of 88% in the left lane (Zimmermann et al., 2014;  $N = 25$ , 1 situation), which is visible in the left, solid black reference bar in Fig. 6. These numbers emerged when using the cooperative system with the instruction “be cooperative” and without time pressure. Now with the “be on time” instruction applying time pressure, the mean acceptance rate dropped to 67% under the baseline (B) condition ( $N = 39$ , 6 situations,  $SD = 30\%$ ), as the solid gray bar in Fig. 6 shows.

The number of accepts dropped significantly under time pressure ( $\chi^2(1) = 4.78, p = .02, \phi = .14$ ) when comparing the decisions to accept or reject between the two experiments. This finding supports H1. However, comparing those two experimental settings is difficult because of the varying number of situations (one vs. twelve) and other confounding factors besides time pressure.

Most of the participants reported during the final interview that they were aware of time pressure. They drove 156 tracks, each comprising the 12 cooperative situations under B,  $S_F$ , and  $S_{E+F}$  conditions, or the respective 18 under the T condition. They completed 79.49% of these in time. All participants arrived in time under  $S_{E+F}$  and T conditions, where they could use reciprocity and points to control the simulated decisions of  $V_L$ 's driver.

Failing to compete the track in time is thus attributable to the environment, namely to the simulated partner's decisions in B and  $S_F$ . When partners rejected cooperation in more than half of the requests (one third category of the foreign acceptance factor), mastering the track in time was impossible (26 cases, 16.66%). Mean overall timeliness was 11.08 s ahead of time ( $SD = 19.11$  s,

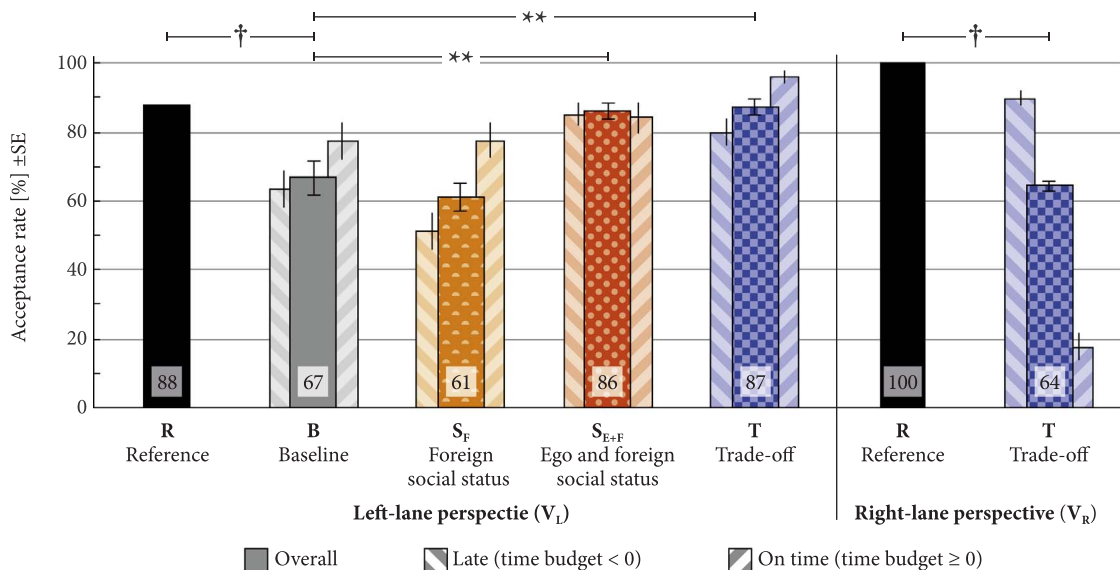


Fig. 6. Comparison of acceptance rates (%) under the reference condition (R, black; Zimmermann et al., 2014) and the conditions under time pressure. The cooperative lane-change assistant: baseline (B, solid gray). Motivational interaction concepts: foreign social status ( $S_F$ , yellow semicircles), ego and foreign social status ( $S_{E+F}$ , orange circles) and trade-off (T, blue squares). The narrow-hatched bars depict the group factor timeliness (current time budget) at the moment of decision. Situation repetitions are different for reference (1), baseline/status (6) and trade-off (9). Error indicators: standard error.  $\chi^2$  test with  $p < .05$  (†), Wilcoxon related-samples signed rank test with  $p < .01$  (★★).

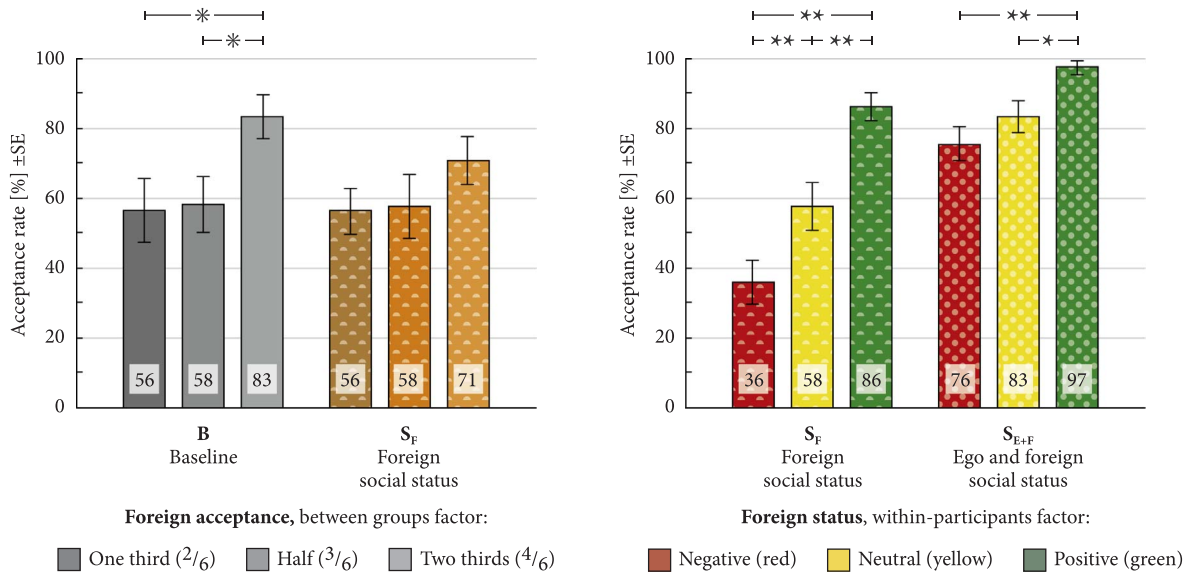


Fig. 7. Comparison of ego acceptance rates (%). Left: Group behavior, split by the between groups factor *foreign acceptance* rates of one third, half, and two thirds. Right: Social information, split by the within-participants factor *foreign status* negative, neutral, positive. Error indicators: standard error. Kruskal-Wallis independent samples test with  $p < .05$  (\*), Wilcoxon related-samples signed rank test with  $p < .01$  (★★) and  $p < .05$  (★).

Mode = 4 s, Min = -44 s, Max = 45 s), which shows that most participants were able to accumulate a considerable time buffer.

We compared acceptance rates for the group factor timeliness, split by the time budget at the moment of the decision during the request phase. These are the narrow, hatched bars for each condition in Fig. 6: left are acceptance rates when being late (*time budget* < 0), the right bars after being on time (*time budget* ≥ 0). Compared to late situations, acceptance rates in the left lane were significantly higher when being on time under the B ( $M_{late} = 63\%$ ,  $M_{on\ time} = 77\%$ ,  $W(22) = 91.00$ ,  $p = .02$ ,  $r = .36$ ), S<sub>F</sub> ( $M_{late} = 51\%$ ,  $M_{on\ time} = 78\%$ ,  $T(22) = 126.00$ ,  $p = .003$ ,  $r = .44$ ), and T ( $M_{late} = 79\%$ ,  $M_{on\ time} = 96\%$ ,  $T(37) = 208.50$ ,  $p = .001$ ,  $r = .37$ ) conditions. No significant difference was found in the S<sub>E+F</sub> condition ( $M_{late} = 85\%$ ,  $M_{on\ time} = 84\%$ ). From the T condition's right-lane perspective, participants were requesting significantly fewer cooperations once they were on time ( $M_{late} = 90\%$ ,  $M_{on\ time} = 18\%$ ,  $T(36) = 0.00$ ,  $p < .001$ ,  $r = -.62$ ).

### 5.2. The effect of group behavior

We analyzed the distributions of ego acceptance rates (also in the left lane) among three independent participant sub-samples, split by the group factor *foreign acceptance*. This is visible in the left part of Fig. 7. Ego cooperative behavior was significantly affected by foreign acceptance rate in the baseline (B) ( $H(2) = 9.26$ ,  $p = .01$ ). Pairwise comparisons (with adjusted p-values) showed that there was no significant difference ( $p > .99$ ,  $r < .01$ ) in acceptance rates between one-third ( $M = 56\%$ ,  $n = 13$ ,  $SD = 33\%$ ) and half ( $M = 58\%$ ,  $n = 12$ ,  $SD = 28\%$ ), but significant ( $p = .27$ ,  $r = .30$ ) differences between each and the two-thirds group ( $M = 83\%$ ,  $n = 14$ ,  $SD = 24\%$ ).

Such a relation (although not significant;  $H(2) = 2.28$ ,  $p = .31$ ) is also indicated under the foreign-social-status (S<sub>F</sub>) condition (see Fig. 7, left), where participants in the two-thirds group seemed to cooperated more often ( $M = 71\%$ ,  $n = 12$ ,  $SD = 24\%$ ) than in the half ( $M = 58\%$ ,  $n = 12$ ,  $SD = 29\%$ ) or one-third ( $M = 56\%$ ,  $n = 15$ ,  $SD = 26\%$ ) groups. That the effect is small and not significant is a hint (besides the small sub-samples) that direct reciprocity is the main effect in S<sub>F</sub>.

### 5.3. The effect of social information

The acceptance rate under the foreign-social-status (S<sub>F</sub>) condition was 61% ( $SD = 27\%$ , see yellow bar with hemicircles in Fig. 6), which is comparable to B. We found an effect within the *foreign-status* factor (see Fig. 7, right): Participants were more likely to cooperate with positive, green cooperation partners ( $M = 86\%$ ,  $SD = 25\%$ ,  $N = 39$ ) than with neutral, yellow ( $M = 58\%$ ,  $SD = 44\%$ ) or negative, red ( $M = 36\%$ ,  $SD = 40\%$ ) ones. The acceptance rate changed significantly depending on the partners' states ( $\chi^2(2) = 30.71$ ,  $p < .001$ ). Pairwise post hoc Wilcoxon tests with Holm-Bonferroni correction show that all three categories differ significantly from each other with medium to large effects ( $p < .007$ ,  $r > .30$ ).

The foreign-status factor also influences decision times in the left lane: response latency increases significantly from green ( $M = 2.56$  s,  $SD = .76$  s), to yellow ( $M = 2.96$  s,  $SD = 1.00$  s) and red ( $M = 3.24$  s,  $SD = 1.41$  s) cooperation partners ( $F(2, 76) = 8.32$ ,  $p = .001$ ,  $r = .31$ ). Pairwise, adjusted comparisons reveal significant differences between green-yellow ( $p = .02$ ,  $r = .43$ ) and green-red foreign states ( $p = .002$ ,  $r = .52$ ), but not for yellow-red ( $p = .40$ ,  $r = .24$ ).

The effect of foreign status is also present under the S<sub>E+F</sub> condition, but with higher acceptance rates than under the S<sub>F</sub> condition

**Table 2**

Matrix of cooperative encounters in  $S_{E+F}$ : Left-lane drivers with their ego status (rows) meet cars having a foreign status (columns). The cells contain accepts per encounters and the resulting acceptance rates (%).

Ego	Foreign		
	Positive (green)	Neutral (yellow)	Negative (red)
Positive (green)	66/69 (96%)	37/46 (80%)	43/59 (73%)
Neutral (yellow)	15/15 (100%)	26/29 (90%)	13/13 (100%)
Negative (red)	–	–	2/3 (67%)

(see Fig. 7, right). The acceptance rates differ significantly between foreign states ( $X^2_F(2) = 15.46$ ,  $p < .001$ ). Pairwise Wilcoxon tests with Holm-Bonferroni correction show that the acceptance rate for green partners ( $M = 97\%$ ,  $SD = 11\%$ ) is significantly higher than for yellow ( $M = 83\%$ ,  $SD = 29\%$ ,  $p = .01$ ,  $r = .32$ ) or red ones ( $M = 76\%$ ,  $SD = 30\%$ ,  $p < .003$ ,  $r = .40$ ), while no significant difference has been found between red and yellow states ( $p = .23$ ,  $r = .14$ ).

#### 5.4. The effect of the social-status interaction concept

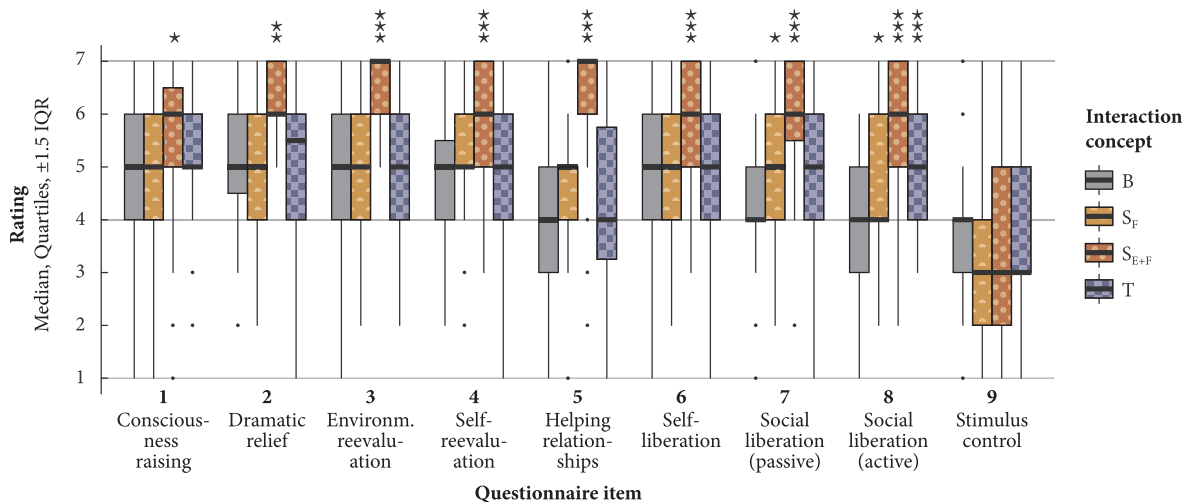
Table 2 shows the distribution of accepts per encounter and the resulting acceptance rate under the ego-and-foreign-social-status ( $S_{E+F}$ ) condition. It separates the encounters in a matrix by ego and foreign status. Except for three yellow-yellow encounters, a neutral, yellow ego state always led to a positive answer to receive the reward. That's why the third, negative row is almost empty (but the same three participants) and a two-factor analysis is not meaningful. However, the acceptance rate is 90–100% for a yellow ego status and unknown for a negative, red one.

Foreign status modulates the acceptance rate only in situations with a positive, green ego status, where drivers applied social control. This is visible in the first row, where acceptance rates are approximately those we have observed in Fig. 7. This leads to an overall  $S_{E+F}$  acceptance rate of 86% ( $SD = 15\%$ ; see Fig. 6, orange bar with circles), which is significantly higher than that under the B condition ( $S_{E+F}-B$ ,  $T(38) = 304.00$ ,  $p < .003$ ,  $r = .43$ ).

#### 5.5. The effect of the trade-off interaction concept

A comparison of trade-off (T,  $M = 87\%$ ,  $SD = 15\%$ ,  $n = 38$ ) and baseline (B) acceptance rates shows a significant acceptance-rate increase in the left lane (see Fig. 6, blue bar with squares; T-B,  $T(37) = 485.50$ ,  $p < .003$ ,  $r = .42$ ). Comparing reference ( $M = 100\%$ ) and T ( $M = 64\%$ ) right-lane decisions shows significantly fewer accepts under T ( $\chi^2(1) = 13.45$ ,  $p < .001$ ,  $\phi = .19$ ).

Cooperation acceptance or rejection decision times from the left-lane ( $M = 2.75$  s,  $SD = .62$  s) and right-lane ( $M = 3.53$  s,  $SD = .66$  s) perspectives differed significantly under the T condition ( $t(37) = -7.29$ ,  $p < .001$ ,  $r = .77$ ). Drivers never ran out of points in our setting. The efficacy of tethering personal benefits, points, to social behavior is visible in the final game scores: initially starting with 100 pt, participants reached at least 83 pt and at most 114 pt ( $M = Mdn = 101$  pt,  $SD = 8.58$  pt,  $Mode = 110$  pt).



**Fig. 8.** Rated concept-questionnaire items. Medians, quartiles (boxes), 1.5\*IQR (error indicators) and outliers (dots). Wilcoxon signed rank contrasts between B and the concepts  $S_F$ ,  $S_{E+F}$ , and T with Holm-Bonferroni adjustment and  $p < .05$  (\*),  $p < .01$  (\*\*), and  $p < .001$  (\*\*\*).



### 5.6. Subjective ratings of behavioral change

Fig. 8 shows a box plot of the median and quartile subjective-item ratings from the concept questionnaire, which we derived from the transtheoretical model. Participants under the B condition generally issued positive ratings ( $rating > 4$ ) in those items, which were associated with raising awareness of their own and foreign cooperative behavior: consciousness raising (item 1), dramatic relief (2), environmental reevaluation (3), self-reevaluation (4), and self-liberation (6).

The social concepts  $S_F$  and  $S_{E+F}$  performed better in those items that were associated with establishing social relationships: helping relationships (5), passive social liberation (7), and active social liberation (8). The first eight items under the  $S_{E+F}$  condition had a  $Mdn \geq 6$ , which was significantly higher than that under the B condition ( $p < .02$ ), with medium to large effects ( $r > .31$ ).

Pure social information (under  $S_F$ ) had a small effect only on the social opportunities and alternatives, because the social-liberation items' (7 and 8) ratings differed significantly from those under the B condition ( $p < .05$ ,  $r > .24$ ). The ratings of the trade-off concept, T, were comparable to those of B. Participants saw increased social opportunity only in active social liberation (8;  $p < .001$ ,  $r = -.43$ ). The participants thought that discontinuing (9) neither of the interaction concepts would have negatively affected the cooperative behavior, although the medians connoted this ( $Mdn = 3$ ).

## 6. Discussion and conclusion

We elaborated a game-theoretic model of cooperative lane changes and tested performance and acceptance of two motivational interaction concepts. Without time pressure, the subjectively perceived value of cooperation dominates the lane-change maneuver for both drivers; those in the right lane requesting a gap, and those in the left lane offering it (Zimmermann et al., 2015). When supported by a cooperative lane-change assistant, drivers in the left lane open gaps to help those stuck in the right lane.

Right-lane drivers strive for lane changes, which help them to advance. This produces an 88% success rate of cooperation similar to our previous study (Zimmermann et al., 2014). In this study, 39 participants drove four interaction concepts in 2086 cooperative lane-change situations.

*Time pressure is effective and restrains cooperation.* We observe less cooperative traffic during everyday driving. Among other things, we determined *time pressure* to be a reason for uncooperative behavior. Three factors (see Section 5.1) support the hypothesized negative impact on cooperation and indicate the efficacy of time pressure on cooperation (H1).

First, time pressure remarkably reduces the acceptance rate of cooperative maneuvers to 67% under our *baseline* (B) condition. Second, the majority of drivers finished the course in time. Third, time pressure relented as soon as drivers estimated that they could arrive in time. This caused them to cooperate more often (either by letting right-lane drivers merge or by not bothering left-lane drivers) once they were ahead of time, even if doing so led to time loss. Hence, we have provided experimental evidence that time pressure is effective: drivers behave rationally and egoistically for their individual advance in traffic.

*Drivers behave indirectly reciprocally to group behavior.* We identified a social dilemma: varying drivers play the *cooperative game* from the left-lane and right-lane perspectives in turn. That said, traffic performance and overall individual performance both benefit from cooperation, but rational, uncooperative left-lane choices decrease performance.

Simulated cars reacted to requests based on a randomized model under both baseline (B) and foreign-social-status ( $S_F$ ) conditions. We modeled three behavioral groups: a less cooperative group of foreign vehicles, which accepted one third of the requests; one reacting cooperatively to half of the six situations; and one accepting two thirds of the requests. We have shown (see Section 5.2), that drivers cooperate more often in cooperative environments (83%) than in mixed (58%) or uncooperative ones (56%). This finding implies the existence of indirect reciprocity (H2.1).

Cooperative group behavior on the road indirectly influences one's own cooperation situation later on. That is: the more one cooperates when one is in the left lane, the more others accept one's requests for cooperation when one is in the right lane. We detected indirect reciprocity only at the extremes, in the one-thirds and two-thirds groups, because the sensitivity was limited by both sub-sample size ( $n \leq 14$ ) and situation repetitions ( $n = 6$ ). It could also imply that positive reciprocity, i.e., gratitude, is stronger and emerges faster at the extremes.

*Social information facilitates direct reciprocity.* Indirect reciprocity involves opportunity and menace at the same time. It could tilt a traffic system toward either total cooperation or none at all. However, potentially cooperative drivers usually meet only once. To allow drivers to decide for cooperation based on a fair criterion other than, e.g., car brand, horsepower, or gender, we introduced an interaction concept. We added *foreign-social-status* ( $S_F$ ) information, which revealed other drivers' past cooperation-related behavior.

When we displayed their prior behavior using a red, yellow, or green social status, participants acted *directly reciprocal* (see Section 5.3). Uncooperative, negatively marked drivers had to endure less cooperation (36%) than medium cooperative, neutral ones (58%), and cooperative, positively marked drivers, who experienced more cooperative reactions (86%).

While we expected social information to amplify reciprocity, we didn't hypothesize changes in the acceptance rates, due to the confounding variables of time budget and modeled group behavior (and the resulting sparse sub-samples). In fact, we neither expected nor discovered a motivational effect since participants still had no incentive to cooperate from the left lane perspective, and group behavior was the same as that in the baseline (B).

The less cooperatively partners acted in the past (causing them to be marked red), the longer the decision times that were observed for accepting or rejecting cooperation. This can be interpreted as response conflict, where processing time is greater when



conflict has to be resolved under cognitive control (for which, according to Kahnemann, 2012, the slow “System 2” is responsible). Following this argumentation, “accept” was the preferred quick response, but drivers wanted to penalize prior uncooperative behavior. The later “reject” is issued to such supplicants following deliberation and thus arrives more slowly.

These results constitute strong evidence that visibility of the cooperation partner’s status results in direct reciprocity (H2.2). This objectifies driving, as cooperation now depends on a comprehensible social criterion.

*Revealed social status motivates cooperation as reward and sanction and makes driving fairer.* Based on the finding that drivers react with indirect and direct reciprocity to cooperation partners’ previous behavior and building on the idea of displaying a social status, we introduced a rule change into the cooperative game. We made the driver’s ego status visible in the *ego-and-foreign-social-status* ( $S_{E+F}$ ) condition in addition to the foreign social status (from  $S_F$ ). Our corresponding game concept rewarded cooperative drivers by improving their status (“carrot” № one) and sanctioned uncooperative ones by downgrading it (“stick” № one) while time pressure was kept constant.

Two factors therefore influenced the driver’s decision: First, by the executive form of social control, social information still led to directly reciprocal acceptance rates in  $S_{E+F}$  (see Section 5.3). Second, by the motivational effect of social control, keeping the individual social status to receive rewards and avoid sanctions, which was visible in increased acceptance rates in  $S_{E+F}$  (see Section 5.4). Drivers were all in all more cooperative due to the latter.

The game model explains why: If a driver refused cooperation, he or she had a higher expectation of getting subsequently penalized. His own behavior and the resulting ego status, accumulated in the left lane, elicited future social control when driving in the right lane. The risk of being sanctioned oneself was the price that a driver had to pay for refusing cooperation. That’s the reason participants “disciplined” other drivers only when they could afford it, i.e., in the green state.

Social control had stronger motivational than executive effects. This led to a high rate of cooperation acceptance (86%) comparable to that in the reference experiment (88% in Zimmermann et al., 2014)—even under time pressure and with non-cooperative traffic involved. This is strong support for the hypothesis that exposed social status motivates cooperation (H3).

*The trade-off interaction concept motivates cooperation and makes it a strategic game.* Our second motivational game concept allowed a *trade-off* (T) between drivers. Drivers in the right lane had to pay points (“stick” № two) to a left-lane driver for opening a gap. The latter were able to earn these points (“carrot” № two) by admitting the right-lane driver in front of them. Hence, the established points system allowed drivers to barter their time for points and vice versa.

The benefit of earning points, which could in turn be invested in cooperative lane changes, was overcoming the drawback of losing  $-1$  s in the left lane. This led to cooperative behavior in the left lane (87%, see Section 5.5). The trade-off concept exerts a motivating effect on cooperation even if the driver is under time pressure (H4).

Participants needed to decide on and pay for a cooperative request during the trade-off in contrast with the other concepts (B,  $S_F$ , and  $S_{E+F}$ ), where requesting gaps was gratis and thus automatically done. The diminishing acceptance rate in the right lane (64%, compared to the 100% acceptance-by-design in Zimmermann et al., 2014) represents the drivers’ strategy for dealing with points.

On the one hand, right-lane drivers wanted to save points for the future. On the other hand, they had to invest them to advance on time. The cooperative strategy is visible in the timeliness factor (see Section 5.1): As soon as right-lane participants were ahead of time, they receded cooperation (18%) to save points. We modeled this aspect in Lütteken et al. (2016): the goals of high scoring, being in time, and driving cooperatively mutually support each other in the trade-off game. Nevertheless, not bothering other drivers with requests for help is also altruistic behavior.

The driver had to strategically estimate the individual advancement vs. the value of points. In the left lane however, the price to pay was constantly  $-1$  s. Depending on the individual points-account balance, accepting the offered conditions was always profitable in the specific situation, but might have been unprofitable in the long run strategy. When it comes to points, it is more blessed to receive than to give; prolonged decision times in the right lane reflect this conflict.

### 6.1. Cooperative and social interaction

*Carrots and sticks influence the driver to the better.* Carrots (rewards) and sticks (sanctions) both motivate cooperation during lane changes regardless of the lane in which they are applied. However, we recommend applying them both, because combination makes them effective. Both social interaction concepts, *social status* and *trade-off*, are able to shape and prime cooperative behavior of humans.

While social-status gives delayed social feedback, the trade-off provides immediate feedback. Intelligent traffic management could take individuals’ prior behavior into account, anticipate their reciprocity, and make cooperation more or less costly based on objective criteria such as traffic density. With such coordination—even though we didn’t model it—a diminishing number of lane changes in the right lane makes sense, e.g., when the right-lane driver’s speed difference relative to the truck is less than that relative to the left-lane column. That gamified interaction concepts work under time pressure demonstrates their motivational potential. They can even compensate the negative effects of time pressure on cooperativeness.

*Subjective perception of a social behavioral change.* Positive ratings have generally shown the cooperative lane-change assistant’s potential for improving social behavior. Drivers were more concerned about their own behavior and its effect on others (see Section 5.6). The *social-status* interaction concept establishing social relationships was perceived as effective in all change processes and was recognized as clearly motivational, especially during interaction with others.

Social information alone didn’t change one’s own cooperative behavior; the social control is causal. This is what we also saw in the acceptance rates. For the *trade-off* concept in contrast, drivers saw increased social opportunities only in the ability to control other road users by offering them points. The subjective report that a discontinuation of neither of the interaction concepts would

have negatively affected cooperative behavior conflicts with our objective findings, which do predict a behavioral change. We assume that acceptance of cooperative maneuvers is different from system acceptance.

While the overall impression was positive, some participants remarked in the final interviews that they would have expected less involvement in automated driving, questioned having to pay or be sanctioned for lane changes, or had the impression that their behavior had even deteriorated due to the social interaction. The last is not supportable from the objective data either.

## 6.2. Applicability and the future

This study demonstrates the effectiveness of rewards (carrots) and sanctions (sticks) in cooperative driving. It may be questioned how such motivational factors will remain effective for longer usage periods. While this is relatively straightforward for a lane-change scenario, a realistic game could live on a variety of game elements and mechanics, such as levels, badges, events, communication, and cues to approach the vision of a social car (Lütteken et al., 2016; Rakotonirainy et al., 2014). We expect changing conditions emerging from the diversity of traffic situations to keep drivers engaged and motivated.

A key challenge will be to supply users with meaningful information about personal and collective benefits relating to social behavior, travel time, energy efficiency and safety, and so forth. Simple criteria such as time/point conditions or social status provided to the drivers can be applied as a surrogate measure. More complicated constructs such as traffic flow, criticality, probabilities, or velocity differences of a plurality of vehicles are too complex for drivers to process, but provides great potential for the underlying intelligent traffic coordination (Wang et al., 2015).

The current study demonstrated effective local cooperation, where the number of obstructed cars—varying between two and four vehicles—was taken into account. Our trade-off system mitigated negative effects, for example time loss, and reduced such obstruction to 64%. As a next step, benefits at the network level can be quantified and optimized using microscopic traffic flow modeling. The social behaviors and interaction observed in this study can help to understand and improve the transport system.

The behavioral effects resulting from social information and control call social networks to mind. A memory of social behavior insinuates a “Facebook on wheels”. Social mechanisms would strengthen strategic and maneuver-based cooperation between traffic participants of different automation levels. The involvement of the driver into strategic decisions of the automated car—to perform a lane change or to give way to other drivers—would feature shared control on the maneuver level and could compensate the side-effects of automation. In any case, our experimental data show that it is possible to manage the negative effects of time pressure in traffic by the introduction of a social currency system. This would foster fairness and balance among traffic participants and involve rule-compliant automated vehicles.

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## Appendix A. The lane-change game

The lane-change game  $\Gamma = \langle N, \Sigma, U \rangle$ , where drivers act as two players  $N = \{V_L, V_R\}$ , having their pure strategy sets  $\Sigma = \{\Sigma_{V_L}, \Sigma_{V_R}\}$  with

$$\Sigma_{V_L} = \{(accept), (reject)\} \quad (1)$$

and

$$\Sigma_{V_R} = \{(change, change), (change, stay), (stay, change), (stay, stay)\} \quad (2)$$

The game is non-cooperative, there being no extensive communication and binding arrangements between drivers. It is sequential in that the left-lane driver plays first by accepting or rejecting the request. The right-lane driver subsequently has the choice of changing or staying in the lane, making it a perfect information game.

The game is furthermore one shot since drivers (most likely) never meet again. The strategy profiles  $(accept, change)$  and  $(reject, stay)$  are cooperative while  $(accept, stay)$  and  $(reject, change)$  are defecting. The payoff,  $U$ , in Eq. (3) depends on the perspective (left or right) and for our baseline scenario represents a time loss of  $-1$  s for  $V_L$  and a time gain of  $11$ – $17$  s for  $V_R$  compared to a non-cooperative situation. This makes the game asymmetric and non-zero-sum:

$$U = \{u(left, time, \sigma_{V_L}, \sigma_{V_R}), u(right, time, \sigma_{V_L}, \sigma_{V_R})\} \quad (3)$$

Eq. (4) formulates the corresponding utility function as:

$$u(perspective, time, request, action) = \underbrace{\psi * spvc(perspective, request, action)}_{\text{Subjectively perceived value of cooperation}} + \underbrace{\tau * time}_{\text{Efficiency}} - \underbrace{\rho * risk(request, action)}_{\text{Safety}} \quad (4)$$

This utility function,  $u$ , maps decisions to the payoff's subjective ordinal utility. It generally takes subjectively perceived value of cooperation, efficiency and safety into account.

**Subjectively perceived value of cooperation.** The function  $spvc$  is deduced in Table 3 and represents the subjective utility of cooperation based on satisfaction, relaxation, accordance, and trust. We model this function from our previous experiment (Zimmermann et al., 2015). It includes individual “comfort” with the lane-change situation and altruistic “conformity” with the

**Table 3**

Subjectively perceived value of cooperation. Utility function  $spvc: perspective, request, action \rightarrow \mathbb{R}$ ,  $perspective \in \{left, right\}$ ,  $request \in \{accept, reject\}$ ,  $action \in \{change, stay\}$ . Values are derived from the standardized mean Anderson-Rubin factor scores (since 0 has a positive notion, it doesn't mean “no utility;” however the ranks are valid on an ordinal scale) in Zimmermann et al. (2015, cf. Fig. 7). We use the *extrinsic* factor, because we interpret its correlation as the utility attributed to situation and partner (Zimmermann et al., 2015, cf. Table II). The subjectively perceived value of cooperation (spvc) is *directly* visible in four tested situations (e.g., in  $L_{Normal}$ ). It's also visible in the two symmetric opposite situation, where we assume the *intrinsic* factor (this symmetry has been shown in section III.C, in  $R_{Decline}$  and  $L_{Abort}$ ). Since we didn't test a forced entry without a prepared gap into the left lane, we argue that this behavior is perceived as disruptive from both perspectives, namely extrinsically defecting (cf.  $L_{Abort}$ ,  $R_{Decline}$ ) and disturbing (cf.  $L_{Brake}$ ,  $R_{Short}$ ).

perspective	request	action	observation	situation	factor	score	spvc
left	accept	change	direct	$L_{Normal/2}$	extrinsic	0.07	1
		stay	direct	$L_{Abort}$	extrinsic	−0.94	0
	reject	change	hypothetic + symmetric	$R_{Decline}$	intrinsic	<−1.17	−2
		stay	symmetric	$R_{Decline}$	intrinsic	−1.17	−1
right	accept	change	direct	$R_{Normal/2}$	extrinsic	0.67	2
		stay	symmetric	$L_{Abort}$	intrinsic	0.06	1
	reject	change	hypothetic	$R_{Decline}$	extrinsic	<−0.83	−1
		stay	direct	$R_{Decline}$	extrinsic	−0.83	0

**Table 4**

Normal-form payoff matrix for the cooperative lane-change game without time pressure ( $\tau = 0$ ) as seen in reference experiments (Zimmermann et al., 2014, 2015). Maximum utility (underlined), strictly dominated strategy (D), dominated strategy (d), Nash equilibrium (e), game solution  $\mathbf{X}$ .

	$\sigma_{V_R}^{(change, change)}$	d	$\sigma_{V_R}^{(change, stay)}$	$\sigma_{V_R}^{(stay, change)}$	D	$\sigma_{V_R}^{(stay, stay)}$	d
$\sigma_{V_L}^{(accept)}$	( <u>1</u> , <u>2</u> ) e		( <u>1</u> , <u>2</u> ) e $\mathbf{X}$	( <u>0</u> , 1)		( <u>0</u> , 1)	
$\sigma_{V_L}^{(reject)}$	(−2 − $\rho$ , −1 − $\rho$ )		(−1, <u>0</u> )	(−2 − $\rho$ , −1 − $\rho$ )		(−1, <u>0</u> )	

partner's advance. It depicts averaged, common knowledge expectations contributed by the partner about the utility of the maneuver. This term gets smaller when partners behave uncooperatively, i.e., cooperation is rejected or maneuvers are perceived as being disruptive or not well coordinated.

**Efficiency** is represented by  $\tau \cdot time$ , where  $\tau$  is the (individually perceived and uncertain) time pressure [1/s], and  $time$  [s] is the objective (public, common knowledge) benefit or loss resulting from the cooperative maneuver. In our scenario,  $V_L$ 's time loss of −1 s when opening a gap is constant.  $V_R$ 's time benefit varies between 11 s and 17 s, when letting a convoy of  $V_L$  and one, two, or three vehicles pass, breaking behind O and accelerating back to 33 m/s. Those figures apply for safety margins of 1 s.

**Safety.** Entering the left lane is dangerous without a gap present; however, the utility depends on individual risk perception  $\rho$  (with  $\rho > 0$ ). We simplify an unavailable gap in combination with an executed lane-change as binary  $risk = reject \wedge change$ .

The payoff,  $U$ , is simplified for our specific lane-change scenario and takes neither surrogate metrics such as distance and velocity (Wang et al., 2015, Eq. (10)) nor safety metrics such as time to collision (Altendorf and Flemisch, 2014, Eq. (9)) into account. Further subjective factors, e.g., fairness, are not modeled. However, we assume time gain, loss, and pressure as predominant measures of efficiency in our setting. Even if comfort were to predominate efficiency, the signs and ordinal ranks are the same: opening a gap is “loss,” changing lane is “gain” in most dimensions (e.g., time, space, comfort, or velocity).

Table 4 depicts the payoff matrix for all strategy combinations in the cooperative lane-change game. Without time pressure ( $\tau = 0$ ), assuming subjective perception to be the single factor ( $\psi = 1$ ), the dominant strategy for  $V_L$  is to accept cooperation. The single dominant strategy for  $V_R$  is to change lane, if  $V_L$  accepts, and to stay in the lane, if  $V_L$  rejects. The strategy combination  $\sigma = ((accept), (change, stay))$  is a Nash equilibrium—neither driver can increase the individual payoff by deviating from his or her choice unilaterally—and is the game's only solution.

This is what we observed in our previous experiments (Zimmermann et al., 2014, 2015). Drivers cooperated by opening gaps and

**Table 5**

Normal-form payoff matrix for the cooperative lane-change scenario under time pressure ( $\tau > 0$ ). Maximum utility (underlined), dominated strategy (d), Nash equilibrium (e), subgame perfect Nash equilibrium (E). Assumptions: risk perception dominating  $\rho \gg \tau > 0$  (R→), time pressure dominating  $\tau > 2\psi > 0$  (P→), subjectively perceived value dominating  $2\psi > \tau \geq 0$  (S→). Game solutions: cooperative ( $\mathbf{X}$ ), defective ( $\mathbf{X}$ ).

	$\sigma_{V_R}^{(change, change)}$	R→d	$\sigma_{V_R}^{(change, stay)}$	$\sigma_{V_R}^{(stay, change)}$	d	$\sigma_{V_R}^{(stay, stay)}$	d
$\sigma_{V_L}^{(accept)}$	( <u><math>1\psi - 1\tau</math></u> , <u><math>2\psi + 11\tau</math></u> ) e		( <u><math>1\psi - 1\tau</math></u> , <u><math>2\psi + 11\tau</math></u> ) S→E $\mathbf{X}$	( <u><math>0\psi - 0\tau</math></u> , <u><math>1\psi + 0\tau</math></u> )		( <u><math>0\psi - 0\tau</math></u> , <u><math>1\psi + 0\tau</math></u> )	
S→d $\sigma_{V_L}^{(reject)}$	(−2 $\psi - 1\tau - \rho$ , −1 $\psi + 11\tau - \rho$ )		(−1 $\psi - 0\tau$ , <u><math>0\psi + 0\tau</math></u> ) P→E $\mathbf{X}$	(−2 $\psi - 1\tau - \rho$ , −1 $\psi + 11\tau - \rho$ )		(−1 $\psi - 0\tau$ , <u><math>0\psi + 0\tau</math></u> )	

changed lanes only when they were offered gaps, following our instruction to “be cooperative.” Defecting, e.g., by  $\sigma = ((\text{reject}), (\text{change}, \text{change}))$ , was not an option both for subjective-perception (*spvc*) and safety reasons ( $-\rho$ ), particularly the latter because of our instruction (“obey the traffic rules”).

Table 5 shows the payoff including the unknown coefficients  $\psi$  (for value perception),  $\tau$  (for time pressure perception), and  $\rho$  (for safety perception). Even if not parameterizing those coefficients, two assumptions allow us to rank preferred strategies based on their ordinal utility.

The payoff matrix shows that  $V_R$  preferably chooses *change* for maximizing utility (the time advance indicated by  $+11\tau$ , which is the waiting time for two passing vehicles) but not at any price. We assume that drivers perceive risk as dominating time pressure ( $\rho \gg \tau > 0$ ). Under this assumption,  $\sigma_{V_R} = (\text{change}, \text{stay})$  will dominate  $\sigma_{V_R} = (\text{change}, \text{change})$ , rendering the threat (*reject*, *change*) not credible. It will be experimentally ensured by the instruction (“obey the traffic rules”) and assumed to be true if right-lane drivers stay in their lane after a reject.

The second assumption concerns time pressure: If time pressure dominates the subjectively perceived value of cooperation ( $\tau > 2\psi > 0$ ), then  $\sigma_{V_L}^{(\text{reject})} > \sigma_{V_L}^{(\text{accept})}$  will lead to defective behavior of  $V_L$ , again by maximizing utility (not losing time,  $0\pi$ ). The subgame perfect Nash equilibrium will thus shift from  $\sigma = ((\text{accept}), (\text{change}, \text{stay}))$  to  $\sigma = ((\text{reject}), (\text{change}, \text{stay}))$ —the driver of  $V_L$  decides the game.

## Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.trc.2018.01.017>.

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