Fakultät für Maschinenwesen
Lehrstuhl für Ergonomie

Cooperative Interaction.
Within Cars and Between Drivers

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Vollständiger Abdruck der von der Fakultät für Maschinenwesen der
Technischen Universität München zur Erlangung des akademischen Grades
eines Doktor-Ingenieurs (Dr.-Ing.) genehmigten Dissertation.

Vorsitzender:
Prof. Dr.-Ing. habil. Boris Lohmann

Prüfer der Dissertation:
1. Prof. Dr. phil. Klaus Bengler
2. Prof. Dr. phil. Martin Baumann

Die Dissertation wurde am 29.01.2018
bei der Technischen Universität München eingereicht
und durch die Fakultät für Maschinenwesen
am 10.09.2018 angenommen.

Dedicated to my family

Contents

Acknowledgment

I wish to thank the fellows, who paved my way en route to this dissertation. First of all, my research-associate colleagues at the Technical University of Munich's multidisciplinary Chair of Ergonomics: Dr.-Ing. Martin Kienle (2014) for introducing me to the institute and the H-Mode project, and evangelizing about cooperative automation; my office mate, Dr.-Ing. Christoph Rommerskirchen (2019), for thrusting me into, supporting me in, and extricating me from the driving simulator; Professor Dr. Armin Eichinger for our inspirational[1] discussions; Dr. Moritz Körber (2019) for methodological[2]; and Dr. Antonia Conti-Kufner (2017) for philosophical ones. I would also like to thank Professor Dr. Cristina Olaverri Monreal for introducing me to the IEEE intelligent transportation systems society[3]; Dr.-Ing. Andreas Haslbeck (2017) for academic carrots and sticks, our unified aviation and automotive approach, and seeding D3CoS; Dr.-Ing. Dino Bortot (2013) for our dive into cross-domain *transporobotics*[4]; and Jakob Reinhardt[5] and Dr.-Ing. Jonas Schmidtler (2019) for singularizing: all robots[6] are equal.

Thanks are due to two unique European research clusters, which painted this work with color: at the D3CoS project, Dr. Andreas Lüdtke (Institute for Information Technology, OFFIS) for his belief in *design patterns* and tireless project-management lessons, and my WP3.3 comrade-in-arms Johann Kelsch (German Aerospace Center, DLR) for fruitful discussions and collaboration; and at the HFauto network, Dr.-Ing. Bastiaan Petermeijer (2017) and Alexander Eriksson, Ph.D. (2017), for our cordial and professional interaction.

Since science is polyglot, I thank Richard Thomas Bartholomew for his meticulous efforts while editing my manuscripts.

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[1] Kahnemann (2012)

[2] Körber, Radlmayr, and Bengler (2016)

[3] and our "Intelligent Cooperative Driving and Autonomous Connected Vehicles" sessions at the Collaboration Technologies and Systems (CTS) conferences

[4] Bengler, Zimmermann, Bortot, Kienle, and Damböck (2012)

[5] Reinhardt, Schmidtler, and Bengler (2019)

[6] Delivery robots, service robots, industrial robots, automated vehicles, and so forth

I am very grateful to my full-strength crew of students. Many thanks for contributing to eye tracking[7], interaction prototyping[8], and other[9] research streams. My thanks to Stefan Bauer, Iris Rothkirch, Larissa Fahrmeier, Markus Weiß, Michael Hochwieser, Konrad Storost, Zhengzhenni Liu, and David Schopf, for their invaluable contributions to the cooperative-interaction concepts and co-authoring! My special thanks to my fellow—finally colleague—Niklas Lütteken, for excelling at the development of sundry user interfaces and his scholar hat trick.

I offer my heartfelt thanks to my parents, Roswitha Zimmermann and Professor Dr. Bernward Zimmermann, for their lifetime of support, their pursuit of education, and their unstinting encouragement.

I am indebted to my academic mentors, Professor Dr. Martin Baumann (Ulm University) and Professor Dr. Ir. Riender Happee (Delft University of Technology), for offering great support and friendly advice in terms of numerous inspirations, comments, reviews, and discourses—anytime and anywhere across Europe.

I owe my greatest debt of appreciation to my mentor and doctoral advisor[10], Professor Dr. Klaus Bengler (Technical University of Munich), for inspiring and advancing this research, for claiming and strengthening its approach, and for mounting both panoramic and macro lenses in its favor, but most especially for offering me reams of great opportunities, thereby challenging and supporting my professional and individual advancement.

Stop creating theories, do something! —Donald A. Norman

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[7] Veronika Petrovych, Philipp Schneider, Natalia Zarawska, Shiyue Liu, Pedro Manuel Aguayo Algar, and Verena Priesack

[8] and the first-generation *Make Your Own App* (myoa.tum.de) MOOC: Annika Stumpf, Lorenz Prasch, Christina Rosenmöller, David Schopf, Niklas Lütteken, Gideon Kloss, Peter Eliseenkov, and Nicolas Härtwig

[9] Leandra Eibl, Konstantin Lehleiter, Jan Liu, Stefan Treml, and Philipp Hugger

[10] *Doktorvater* is the appropriate German designation

Abstract

This publication-based doctoral dissertation explores interaction concepts for cooperation. Specifically, it investigates social cooperation between drivers as well as human-machine cooperation between cars and their drivers. The research goals—design of cooperative interaction, investigation into its subjective perception, and motivating humans to cooperate—are based on lane changes. Human-centered design methods govern a game-theoretic analysis, multimodal design, iterative implementation, and driving-simulator evaluations of the final interaction concepts for cooperative driving. Five papers pursue these research goals and the dissertation ultimately proffers ten cross-domain-applicable design recommendations.

Keywords Cooperative driving, human-machine interaction, social interaction, automated driving, connected vehicles, lane-changing

1 Cooperation

Cooperation is a policy observed in genomes, between cells, in organisms, among animals, and in particular between humans. On a small scale between hunters and gatherers, and on a grand one among nations, humans are well versed in the game of cooperation and its opposite, defection. (Nowak, 2006)

From the behavioral-sciences perspective, Argyle (1991, p. 4) defines cooperation among humans as "acting together, in a coordinated way at work, leisure, or in social relationships, in the pursuit of shared goals, the enjoyment of the joint activity, or simply furthering the relationship." Such cooperative behavior strives toward individual or altruistic rewards, builds on relationships, and is fostered by coordination (Argyle, 1991). Interaction is just a means for achieving these *cooperative goals*.

From the computer-science perspective, in contrast, cooperative systems are ideally designed, implemented, and evaluated around their human use, with interaction "between one or more humans and one or more computational machines" (Hewett et al., 1992, p. 5). Usable systems stand out by virtue of their user, rather than their system centricity. Interaction is essentially a gatekeeper between functionality and the *users' goals*.

Yet when the two perspectives merge, cooperation is no longer exclusively about human behavior: both worlds interact. Hollnagel and Woods (1983) approach this situation from a cognitive-systems-engineering perspective and address human-machine systems, which produce adaptive, goal-oriented, intelligent action. Researchers tailor such joint actions and goals specifically toward their use-cases. Flemisch, Bengler, Bubb, Winner, and Bruder (2014, p. 345) envision cooperative driving as "working together of at least one human and at least one computer on the guidance and control of at least one vehicle." Schmidtler, Knott, Hölzel, and Bengler (2015) render cooperation as an interaction paradigm with the joint criteria of time, space, and aim between a human and a machine robot. Those definitions determine actors (drivers, workers, and so forth) and assume a shared goal between cooperators.

Drivers and their cars presumably share the goal of being safe, for example. Workers and their industrial robots may share the goal of task completion. But the remarkable characteristic of cooperation is the cooperators' ability to formulate individual goals (Krüger, Wiebel, & Wersing, 2017). Cooperation involves mental models of one's own and other cooperators' states and an anticipation of the latters' future states to combine strategies and achieve a payoff (Krüger et al., 2017). This is defined by evolution, where any cooperator "pays a cost […] for another individual to receive a benefit" (Nowak, 2006, p. 1560).

On one hand, technical systems are becoming smarter and more capable of formulating their own goals (algorithms seem to be a promising way out of the crisis surrounding Moore's thwarted law; Aimone, 2017). They're beginning to cooperate just like humans do, and Ishiguro's androids are showing their ability to even build relationships (Mar, 2017).

On the other hand, more and more simultaneous stakeholders are appearing on the cooperative stage. Humans are fostering tight-knit interaction in social networks such as Facebook, as are devices in the Internet of Things (Ashton, 2009).

Cooperation can happen in any constellation between humans, between machines, between humans and machines, and also between human-machine entities. Each stakeholder formulates its own goals. Hoc's (2001, p. 515) definition of multi-agent cooperation takes this into account:

> *Two agents are in a cooperative situation if they meet two minimal conditions. (1) Each one strives towards goals and can interfere with the other on goals, resources, procedures, etc. (2) Each one tries to manage the interference to facilitate the individual activities and/or the common task when it exists. The symmetric nature of this definition can be only partly satisfied.*

Its generic definition, not restricted to human-human nor human-machine interaction, allows the holistic investigation of cooperation on roads, within cars, and between drivers. In this dissertation, the author sketches a vision in which both perspectives are deeply interconnected and where neither works without the other. To facilitate cooperation *between drivers* of different vehicles, a common goal needs to be established within those cars (i.e., cooperation between human and machine). Conversely, other drivers' goals need to be taken into account (i.e., cooperation between road traffic) to establish cooperation *within cars*.

1.1 Within cars: human-machine cooperation

For reasons of safety, increasing traffic density, and comfort—and thanks to advances in data acquisition and processing technologies—we are quickly heading from driver assistance systems toward automated driving (Bengler et al., 2014; Kyriakidis, Weijer, Arem, & Happee, 2015). Meanwhile, restricted system capabilities, situational complexity, safety risk, or traffic density for example still render some situations such as freeway entry or lane changes (between traffic participants driving with different levels of automation) difficult to handle when driving *conditionally automated* (SAE International, 2016).

The human is required to take control here, which is the *fallback* (SAE International, 2016). The human operator will be considered a *backup* in the medium-term future (e.g., BMW; Gold, Damböck, Lorenz, & Bengler, 2013) or a *bug* to be fixed (e.g., Google; Urmson, 2015a) and *replaced* by complete autonomy sooner rather than later (e.g., Tesla; Korosec, 2015).

However, after the first driver was killed in a 2016 accident involving an activated "autopilot" (partial-automation in SAE International's nomenclature, 2016), the vendor emphasized the "public beta" character of the feature and the driver's responsibility: "Always keep your hands on the wheel. Be prepared to take over at any time" (The Tesla Team, 2016). Banks, Plant, and Stanton (2018) attribute this to "designer error" rather than "driver error." Consequently, contrary to these erroneous designs, the sequel argues for cooperative driving within and between cars.

Relieving the driver of the driving task is not necessarily helpful. As observed in aircraft (Wiener & Curry, 1980) and industrial automation, attempting to replacing the unreliable, inefficient human entails the *ironies of automation*—an expression coined by Bainbridge (1983): The higher the level of automation, the more important is the human stake. Norman (1990, p. 585) identifies "inappropriate feedback and interaction, not 'overautomation'" as "the 'problem' of automation."

Design issues, system unreliability, and system boundaries oblige operators to monitor automated systems and to assume control whenever expedient. Flagging vigilance (with potentially visible effects within 30 minutes; Cabrall, Happee, & de Winter, 2016; Molloy & Parasuraman, 1996) and skill deterioration (Bainbridge, 1983) cause humans to monitor poorly. Response times prolonged by 1–1.5 seconds (Young & Stanton, 2007) and noticeable automation effects after seven seconds (Gold et al., 2013) have been reported after a driver assumes control from a driving automation system. Operators of highly automated systems are unable to effectively assume control especially if information is lacking or incorrect (Eriksson & Stanton, 2015).

Hence, instant transition back to full manual operation raises performance and safety issues. That a driver can fulfill the role of fallback operator or an automated system evinces the "clairvoyant" skills needed for timely reaction to takeover requests are both doubtful.

Human-machine cooperation is a superior interaction paradigm for automation. Instead of forcing human operators out of the loop, machines should continually interact with them "in a normal natural way" (Norman, 1990, p. 590), and provide feedback to enable detection, correction, and alertness retention. An automated system would ideally discuss activities with its human operator in a "joint problem-solving" way (p. 591). Sarter and Woods (1995, p. 15) call this cooperative strategy "management by consent." An automated system needs to support “reliable and timely conflict detection and resolution” (W. A. Olson & Sarter, 2001, p. 263). This in turn requires transparent interaction among all partners involved (W. A. Olson & Sarter, 2001).

Hoc, Young, and Blosseville (2009, p. 136) identify the need for automated systems to “support the human operator as part of a team, rather than replace them” and argue for human-machine cooperation from a multi-agent perspective thereby establishing a framework of modes and levels of cooperation (Hoc, 2001; Hoc et al., 2009). A cooperative system should “act as a human co-driver” (Hoc et al., 2009, p. 154) where both human and machine communicate their goals and intentions (e.g., by mutual control). Abbink, Mulder, and Boer (2012) recommend that a driver should remain permanently in control, receive feedback, interact with, and benefit from the automation. Bengler, Zimmermann, Bortot, Kienle, and Damböck (2012) argue for *shared authority* in dynamic situations. Walch et al. (2017, p. 280) consider driver and automation to be team players by requiring “mutual predictability” to enable each to anticipate the others’ actions, “directability” of partners’ actions, a “shared situation representation” for coordination, and “trust and calibrated reliance” shared within the team.

Many research groups now investigate interaction concepts under names such as distributed cognition (Hollan, Hutchins, & Kirsh, 2000), human-machine cooperation (Hoc, 2001; Hoc et al., 2009), adaptive automation (Hancock et al., 2013; Sheridan & Parasuraman, 2005), copilot (Bellet, Hoc, Boverie, & Boy, 2011), shared control (Abbink et al., 2012; Flemisch et al., 2014), cooperative guidance, H-Mode, or Conduct-by-Wire (Damböck, Kienle, Bengler, & Bubb, 2011; Flemisch et al., 2014), or from the cross-domain transportation (Lüdtke et al., 2012) or even transportation-and-robotics perspective (Bengler et al., 2012). The cooperative automation that the author proposes in this dissertation builds on H-Mode, due to its natural haptic and visual interaction within cars.

1.2 Between drivers: traffic cooperation

Road-traffic cooperation is established normatively nowadays. German road-traffic regulations, for example, require drivers to exhibit mutual respect (StVO, 2013, §1 (1)) and to engage in behavior that minimizes the impairment, endangerment, obstruction, and harassment of others (StVO, 2013, §1 (2)). Drivers can resort to a number of interaction modalities to facilitate cooperation, for example human gestures such as nodding or waving, their driving style, and braking or opening gaps, then using signals such as the turn signal or horn.

Overtaking for instance requires cooperation between the overtaking vehicle, the vehicle being overtaken, and—in the worst case—the oncoming vehicle. Hence, German law regulates the cooperative situation and demands for high speed difference resulting in adequate maneuver utility; for communication of intent using turn signals, headlight flasher, and horn; and for the obligation of a vehicle being overtaken to cooperate by maintaining or decreasing its speed (StVO, 2013, §5).

The problem with this is twofold. First, communication of intent is ambiguous (e.g., a light indicator's various meanings) and the misunderstanding of cooperative goals ensues (cf. Benmimoun, Neunzig, & Maag, 2004). Second, the cooperation's utility is subject to the cooperators' individual evaluation—and so is the cooperation's goal. Drivers hold a subjective perception of, and only a limited perspective on, the traffic system's performance (cf. Benmimoun et al., 2004). Herein lies the potential for technologically mediated, social cooperation.

Traffic coordination features safety and performance improvements. Individual vehicles will be pivotal for the introduction of automation onto public roads (Shladover, Su, & Lu, 2012; van Arem, van Driel, & Visser, 2006). Platoons of vehicles will be able to use cooperative automation achieved through vehicle-to-vehicle (V2V) communication to operate at reduced following distances (Ploeg, van de Wouw, & Nijmeijer, 2014). They can form cooperative groups that decide on optimal cooperative maneuvers (Frese, Beyerer, & Zimmer, 2007).

A capacity gain of up to 25 % is reported in three-lane merging and weaving when using autonomous intelligent cruise control systems (depending on penetration rate, Minderhoud, 1999). Ultimately, vehicles connected through vehicle-to-vehicle and vehicle-to-infrastructure (V2I) networks form an intelligent vehicle/highway system (IVHS; Varaiya, 1993) or cooperative intelligent transportation system (C-ITS; Aramrattana, Larsson, Jansson, & Englund, 2015). The goal is to improve safety and efficiency, e.g., by detecting congestion (Bauza, Gozalvez, & Sanchez-Soriano, 2010), coordinating lane changes and car-following (Wang, Hoogendoorn, Daamen, van Arem, & Happee, 2015), or resolving stop-and-go waves (Wang, Daamen, Hoogendoorn, & van Arem, 2016). A combination of V2V and V2I systems could prevent 81 % of all vehicle crashes (Najm, Koopmann, Smith, & Brewer, 2010). Such traffic cooperation could enhance all levels of automation (including manual driving; or even cooperation with manually driven cars, Gauerhof, Alexander, & Lienkamp, 2015).

Driving is social interaction. Driving involves (and will involve) social norms, needs, and contexts (Fleiter, Lennon, & Watson, 2010; Rakotonirainy, Schroeter, & Soro, 2014). For example, some drivers tend to hinder foreign (amongst them automated) vehicles from cutting in (Zheng, Ahn, Chen, & Laval, 2013). Aggression (Rakotonirainy et al., 2014; Zheng et al., 2013), frustration, stress, disadvantage (Zimmermann et al., 2015), unfairness, incomprehension, or unawareness (Rakotonirainy et al., 2014) could be the reason that disrupts cooperation.

To countervail those factors, shared information (Rakotonirainy et al., 2014), shared intentionality (Tomasello & Carpenter, 2007), trust (McKnight & Chervany, 2001), control (Das & Teng, 1998), voluntary decisions (Heesen, Baumann, & Kelsch, 2012), willingness (Hidas, 2005), and driver-initiated control (Banks & Stanton, 2016) have to form the basis of cooperation.

The human stake in coordinated traffic. Traffic coordination is the machine's distinctive skill. The complexity and fragility of traffic-flow optimization render it an algorithmic challenge. Social interaction is the human's unique contribution on the other hand. Automation might be able to arbitrate, execute, and optimize cooperative maneuvers independently from humans; however, due to the human incomprehensibility of such optimizations, its consequently intransparent feedback, the aforementioned automation effects, and the social component of cooperation, any traffic coordination will necessarily lead to human involvement.

So as not to revoke ideal maneuvers and to optimize performance instead, a *common frame of reference* (Hoc et al., 2009) between human and machine is fundamental. This in turn requires the user to be in control (Banks & Stanton, 2016). Instead of fobbing off the implementation or recovery of a cooperative maneuver onto the human, a cooperative system should involve its driver preemptively. Only joint awareness of maneuvers and reliable agreements between (human or machine) traffic participants will lead to each complementing the others. In this dissertation, the author will establish such technologically mediated, cooperative maneuvering between drivers.

1.3 The lane change as a use-case of cooperation

Since this work aims at exploring cooperative interaction from two perspectives—human-machine cooperation (within cars) as a driver interacting with automation, and as social cooperation among interacting traffic (between drivers)—a suitable use-case, following Geyer et al.'s (2014) ontology, is essential. Table 1.1 shows a taxonomy of situational elements in order of their increasing complexity (based on Flemisch et al., 2014).

Lane changes in human-machine cooperation. When clustered by modes of cooperation (according to Hoc et al., 2009), nowadays there are systems that assist or automate the driving task (according to SAE International, 2016) for the situational elements "speed," "distance," and "curve." After Otto Schulze patented the eddy-current speedometer in 1902 (Wesner, 2005), cars were able to augment human perception by indicating speed. At the other end of the cooperation scale, the automation required to reliably manage "overtake" situations (at least level 3 according to SAE International, 2016) is still at the cutting edge

Table 1.1: Taxonomy of situational elements with increasing level of complexity (based on Flemisch et al., 2014), and their mapping to driving levels (according to Donges, 1982; Michon, 1985) and dimensions of driving. Hoc et al.'s (2009) human-machine cooperation modes on the action level display interaction between drivers and automated systems (mapped to SAE International's automation levels, 2016, where applicable) across situational elements. Traffic cooperation across situational elements displays interaction between different road users. Existing systems are printed in black, those in scope of this research are in blue/italic, and future systems are gray.

Situational element	**speed**	**distance**	**curve**	**overtake**	**oncoming**	**crossing**
Level of complexity	→					
Level of driving	operational/control			tactical/maneuvering		
Dimension of driving	longitudinal		lateral		longitudinal & lateral	
Human-machine cooperation						
Perception	speed indicator	distance indicator	road-curvature indicator	blind spot indicator	long-range indicator	surrounding traffic indicator
Mutual control						
Warning	speed warning	distance warning	lane-departure warning	collision warning	collision warning	
Action suggestion	active accelerator pedal		active steering wheel	***lane-change suggestion***	evasive-maneuver suggestion	crossing suggestion
Limit	speed limiter	emergency brake	lane-departure prevention	lane-change prevention	minimal risk condition (SAE 4+)	
Function delegation						
Mediation	cruise control	adaptive cruise control	lane-keeping assistant	***lane-change assistant***	fallback performance (SAE 4+)	
Control	acceleration (SAE 1+)	acceleration (SAE 1+)	steering (SAE 1+)	lane change based on environment monitoring (SAE 3+)	driving-mode dependent (SAE 3+)	
Traffic cooperation	intelligent speed adaptation	cooperative adaptive cruise control	/	***cooperative lane-change assistant***	cooperative obstacle forwarding	cooperative interlocked crossing

(Walker, 2017) when discussing function delegation. Although Tesla's "autopilot" can execute user-initiated lane changes (Harwell, 2015) during partial automation (level 2), the first conditional (level 3) automation, which Audi announced for 2018, will still require manually executed lane changes (Paukert, 2017). From the perspective of human-machine cooperation, there's still a lack of suggesting and mediating lane changes (see blue cells in Table 1.1).

Lane changes in traffic cooperation. Traffic cooperation on the other hand, where vehicles cooperate among each other or with infrastructure, isn't implemented yet although there have been field studies focusing on intelligent speed adaptation (European Commission, 2017) and research on cooperative adaptive cruise control (cACC; de Bruin, Kroon, van Klaveren, and Nelisse 2004; Shladover et al. 2012; van Arem et al. 2006; Wang et al. 2016). The cooperative lane-change assistant (cLCA; see blue cell in Table 1.1) however is new and has recently been investigated (Kelsch, Dziennus, & Köster, 2015; Wang et al., 2015; Zimmermann et al., 2014).

Lane changes are safety critical. Lane changes are safety critical, frequent, and complex maneuvers (Ammoun, Nashashibi, & Laurgeau, 2007; Heesen et al., 2012), which are responsible for one fifth of US freeway fatalities (Golob & Recker, 2004; Pande & Abdel-Aty, 2006). Their main causes are human recognition and decision errors (Knipling, 1993; Treat et al., 1979).

Lane changes provide optimization potential. Although lane-departure warning systems could avert some of these fatalities (Jermakian, 2011), lane changes impose a major restriction on traffic performance (Ahn & Cassidy, 2007; Zheng et al., 2013). Traffic performance, throughput, and flow would benefit from cooperative lane-change coordination via V2V or V2I networks (Farah et al., 2012; Moriarty & Langley, 1998; Wang et al., 2015).

Lane changes are the next challenge. Hence, with the ultimate goal of improving safety and performance in road traffic, both human-machine and traffic perspectives of cooperation emerge during the lane change. This use-case is exemplary for involving coordination and interaction between drivers and a driver and his or her car. From both perspectives, it is also the next challenge in both research and development (according to Table 1.1). The lane-change use-case is versatile in that it generalizes the "overtake" situation and extends it by comparable maneuvers such as weaving (between lanes, at interchanges, before crossings) and merging (at on-ramps, exits, ending lanes, obstacles, or accidents).

The cooperative lane-change scenario. To mitigate the aforementioned human recognition and decision errors (on board), and to establish a driver's willingness and ability to cooperate (between drivers), anticipation of the lane-change maneuver (Heesen et al., 2012), which in turn requires 8–14 seconds (Zheng et al., 2013), is important. Hence, the author

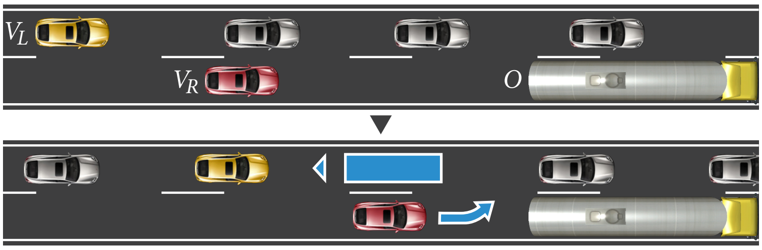

Figure 1.1: A driver in the left lane (V_L, yellow) offers a gap (blue) to the right-lane driver (V_R, red), before the latter rear-ends an obstacle (O). Source: Zimmermann et al. (2018).

of this dissertation focuses on timely, anticipatory coordination of lane-change maneuvers. Fig. 1.1 shows the cooperative lane-change scenario: the vehicle's driver in the fast lane, V_L, receives a request to brake for the vehicle in the slow lane, V_R. A gap emerges when the former accepts cooperation, which allows V_R to safely merge.

1.4 Research goal: improve cooperative interaction

Goal of this doctoral dissertation is to measurably improve cooperative interaction within cars (human-machine cooperation) and between drivers (traffic cooperation). Lane-change maneuvers on highways serve as a relevant use case in that safety, efficiency, and comfort could be improved by their enhanced anticipation (i.e., traffic cooperation) and rectified implementation (i.e., human-machine cooperation). Put differently, to render lane changes safe, efficient, and comfortable within cars, those improvements need to be established between drivers of different cars in the first instance. Such improvement—by mutual interference (Hoc, 2001) and communication of goals (Norman, 1990) through interaction—requires technological solutions for supporting the interaction from both perspectives. The following research questions emerge from this undertaking:

Cooperative interaction. What interaction design and interaction timing are suitable to support cooperative lane changes (in both lanes, between drivers, as well as between human and machine)? What does an innovative cooperative user interface look like, and how much does it improve safety and support the ability to cooperate?

Subjective perception of cooperation. Do situational factors (timing and success) affect cooperation? How can subjective perception of cooperative situations be measured, and what is the driver's subjective perception of cooperative lane-change maneuvers?

Motivation of cooperation. Is cooperation subject to individual (time pressure) and social (behavioral) factors? Which interaction concepts can motivate cooperation, and do they support the willingness to cooperate?

These questions are user centric, as are the empirical experiments that are essential to answering them. Users assume a driver's role in the context of those research questions; therefore, they have to drive its prototype to form an understanding of technologically mediated cooperation. A series of driving-simulator experiments is hence required to *render cooperation experienceable* for drivers virtually.

To excite such experience in the driving simulator, this dissertation's overall methodological approach loosely follows that of Norman's (1990) human-centered-design process. It begins with observation (*analysis*), continues to creative ideation (*design*), leads to prototyping (*implementation*) of interaction concepts, and culminates with testing (*evaluation*) in the driving simulator; then the process iterates. Each group of research questions depicts one iteration and will engender a corresponding driving-simulator study. The granular approaches, methods, and the final concepts' big picture—utilized across all three iterations—are described in chapter 2.

Five publications report methodological and design specifics and answer these research questions, since this doctoral dissertation is publication-based. The first iteration targets the analysis and design of the basic *cooperative interaction* concept in Zimmermann and Bengler (2013; for a summary see chapter 3.1) and its implementation and evaluation in Zimmermann et al. (2014; see chapter 3.2). The second iteration is dedicated to the *subjective perception of cooperation*, as discussed in Zimmermann et al. (2015; see chapter 3.3). The game concepts described in Lütteken et al. (2016; see chapter 3.4) and Zimmermann et al. (2018; see chapter 3.5) finally cover the third iteration, which concerns *motivation of cooperation*.

Chapter 4 summarizes results from all iterations. Chapter 5 derives design recommendations for cooperative systems. In conclusion, chapter 6 discusses implications for the future.

2 Human-centered design of a multimodal interaction concept

This chapter's narrative is modeled on Sinek's (2011) golden circle. It explains *why* this research has been undertaken, spotlights the major methods of *how* it was conducted, and finally presents *what* its outcome was. The last, the final multimodal interaction concept, spans a consistent big picture (presented in blue boxes) across all research questions and iterations (see chapter 1.4). In that human-centricity guided the design process en route to the big picture, each stage spots its respective golden circle: analysis (see chapter 2.1), design (2.2), implementation (2.3), and evaluation (2.4).

2.1 Analysis

The goal during this stage is a structured analysis of cooperation, its challenges, and an ideation of corresponding solutions. A (cross-domain) analysis of cooperation requires a common—design patterns—language. In particular, this uses formal models to support understanding and quantification of the status quo of cooperation and its communication processes: from the human-machine interaction perspective by using interaction sequences, from the social perspective by using game theory. Beyond that, the interaction and game-theoretic models ultimately enable the formation of cooperative interaction, by using rule changes applied to the game, and by an optimized interaction sequence.

Cross-domain literature review, workshops, and design patterns. This work contributed to the European D3CoS project (Lüdtke et al., 2012), which explored cross-domain cooperation for transportation systems. The tool for structuring cooperative problems (Baumann et al., 2014a) determined the lane-change scenario and the research question of cooperative interaction. Bengler, Zimmermann, Bortot, Kienle, and Damböck (2012) elaborated *interaction principles* for cooperative human-machine systems from a cross-domain transportation and robotics perspective and embedded human operators of automated systems into a model incorporating five layers of cooperation: intention exchange (cf. Tomasello &

Carpenter, 2007), cooperation mode (cf. Hoc et al., 2009), task allocation (cf. Kelsch, Temme, & Schindler, 2013), user interface (cf. Flemisch et al., 2014), and physical contact (cf. Bortot, 2013).

Zimmermann and Bengler (2013) subsequently employed these layers to decompose the lane-change scenario into intention, cooperation, allocation, interaction, and interface. Various domain-specific automotive and cross-domain transportation workshops contributed to cooperative solution strategies (Baumann et al., 2014a). Baumann et al. (2014b) cast the solution strategies as *design patterns.* These served two purposes during the analysis phase: observation of the interaction concepts described in this theses (e.g., "explicit addressing"), and the dissemination of proven solutions into the project (e.g., "directed information").

Interaction in Unified Modeling Language. Zimmermann and Bengler (2013) describe the approach taken to sketch cooperative interaction based on these design problems, principles, and patterns in the form of activity, sequence and state diagrams expressed in unified modeling language (UML; Rumbaugh, Jacobson, & Booch, 2010). The method helped to identify interaction sequence, interaction phases, transitions, necessary human decisions, information semantics, and time constraints. Perception-response times (Caird, Chisholm, Edwards, & Creaser, 2007; P. L. Olson & Sivak, 1986), takeover times after automated driving (Damböck, 2013; Gold et al., 2013), safety margins issued in the road traffic act (StVO, 2013, §4), comfortable deceleration (Chakroborty & Das, 2004), and lane-change maneuver observations from naturalistic driving (Olsen, Lee, Wierwille, & Goodman, 2002; Salvucci & Liu, 2002) served as foundation for interaction timing. Zimmermann and Bengler (2013) explored the interaction phases and Bauer (2013) calculated their duration.

Game-theoretic model. Inspired by game-theoretic traffic analyses (Hollander & Prashker, 2006) and more recently, control (Altendorf & Flemisch, 2014; Wang et al., 2015; Zohdy & Rakha, 2012), Zimmermann et al. (2018) model the lane-change scenario as a game. The model identifies the effects of time pressure on rational behavior and recognizes a social dilemma (Fehr, Fischbacher, & Gächter, 2002; Messick & Brewer, 1983) that arises during unbalanced lane change. To motivate cooperation (the third research question), a social information game (Kollock, 1998; Rakotonirainy et al., 2014) as a moderator of direct reciprocity (Nowak & Roch, 2007), and a strategic trade-off game introduce a counterbalance. Lütteken et al. (2016) simulate the latter game model and Zimmermann et al. (2018) describe both motivational games.

Big picture: the model of cooperative interaction

Table 2.1 provides the model of cooperative interaction, which flows through the phases request, suggest preparation, prepare, suggest action, and action. This is the minimal semantic interaction needed to find a cooperator, open a gap, and change the lane (Zimmermann & Bengler, 2013). The cooperative interaction controller (either implemented as superordinate V2I authority, or a distributed V2V network; see the design patterns set "resource allocation" in Baumann et al., 2014b) senses that the right-lane vehicle, V_R, is approaching an obstacle, O, and determines that the left-lane vehicle, V_L, is a suitable cooperator (see scenario in fig. 1.1). Eligibility is calculated based on time, distances and differential speed (Bauer, 2013).

Table 2.1: Cooperative interaction phases, their duration, and phase transitions, as designed in the studies by Zimmermann et al. (years in parentheses).

Interaction phase		**Phase duration**		**Phase transition**
(2013)		(2014; 2015)	(2018)	
I	**Request**	4.0 s	6.3 s	V_L accepts (and V_R partly requests)
II a	Suggest preparation		13.2 s	V_L brakes (automatically)
II b	**Prepare**	9.0 s		V_L prepared the gap
III a	Suggest action	4.0 s	4.2 s	V_R steers
III b	**Action**	6.0 s	6.3 s	V_R changed lane
Total		23.0 s	30.0 s	

May I bother you? The driver of the left-lane vehicle, V_L, receives a request to cooperate and decides based on maneuver recognition (in Zimmermann et al., 2014), maneuver perception (in Zimmermann et al., 2015), or social, tactical, or strategic game criteria (in Zimmermann et al., 2018). Since cooperation was subject to a charge in Lütteken et al. (2016), the right-lane driver also had to request cooperation in V_R during this phase.

Prepare a gap! Once V_L's driver accepts cooperation, the cooperative system suggests preparation of cooperation by the "open a gap" maneuver. The sequence is flexible in that maneuvers are exchangeable with "accelerate" or "change lane" for example. V_L's driver in the scenario accepts the suggestion by braking. Since deciding for cooperation went along with braking in Zimmermann et al. (2014), the first two phases merged there. As the driver had to process additional social information and make the resulting decision in Zimmermann et al. (2018), the latter necessitated separate phases. However, the request phase duplicated the decision to “brake” in suggest preparation after a preceding “accept.” Hence, the suggest preparation and prepare phases merged in Zimmermann et al. (2018) in that the automation executed the braking maneuver. The prepare phase depicts the opening of a gap by coasting.

Change lanes! As soon as the gap is established, V_R suggests the cooperative action to its driver—to perform a lane change. Once V_R's driver made the decision to change lane, the action phase accompanies the maneuver and completes once V_R is in the left lane.

Interaction sequence. Since the phases follow the causality of a lane change, they have to be executed in order of request cooperation (I), prepare the gap (II), and perform the lane-change action (III). A cooperative request (I) can be formulated as a gap-opening suggest (II a) and hence be merged with the latter. The phases suggest preparation (II a) and suggest action (III a) involve the driver (for the user being in control and a common frame of reference), are necessarily suggested before the action, and require human decision times in turn.

Transitions and timing. Phase transitions are consistent across all studies, adding up to interaction times of 23 s and 30 s respectively to anticipate cooperation. The cooperative interaction controller initiates the request phase 23 s to 30 s before V_R reaches the obstacle's safety margin (1 s headway); the latter being the time to breakup (TTB). TTB is constantly evaluated against the maximum phase durations (see table 2.1). Phases start sequentially upon a preceding phase transition, following the cooperative-lane-change-assistant storyline in the subsequent section 2.2. If the remaining phases' duration exceeds the TTB, the driver doesn't implement the maneuver suggestions (by accelerating or changing lane), or the driver rejects (by pressing a paddle), then the cooperation is aborted. Zimmermann and Bengler (2013) derive information semantics subject to the human-machine interaction, which lays the foundation for the following interaction design.

2.2 Design

The design goal is to convert models and games supporting cooperation (from the analysis in chapter 2.1) into useful interaction (i.e., interaction combining usability and utility; Nielsen, 2012) and streamlined user-interface designs intended for in-vehicle application. The design stage focuses on creating a variety of low-cost, prototypical designs intended to establish the interface elements in their respective communication modalities. Their visualizations are intended to make abstract cooperation models tangible for users (and designers) and to foster the design cycles' rapid iteration.

Usability engineering technique. This work's author drew upon Nielsen's (1994) *guerrilla human-computer interaction (HCI)* discount usability engineering techniques such as vertical prototypes peppered with *Wizard-of-Oz* interaction, which are rapidly iterated by *thinking aloud* and *heuristic evaluations* (Nielsen, 1993; Norman, 1988). The interaction design prototypes ranged from paper-and-pen sketches, Photoshop images, HTML5 dummies, and Powerpoint sequences to video animations. Zimmermann et al. (2014) show an example; students' theses provide more details (Hochwieser, 2015; Liu, Schopf, Storost, & Zimmermann, 2015; Lütteken, 2013; Lütteken & Zimmermann, 2016; Weiß, 2015).

Natural interaction, multimodality, and augmented reality. Automated systems should feature natural interaction and feedback (Norman, 1990). Multimodality, according to Wickens' stimulus–central processing–response (Wickens, Sandry, & Vidulich, 1983) and multiple resources (Wickens, 2008) theories, supports this goal. Active actuators (Mayer, 1986), such as an active yoke steering wheel (Kienle, 2014), provide a haptic display in the kinesthetic and tactile sensory modalities. The contact-analog head-up display (Bubb, 1975) is an optical enabling technology for augmenting the visual modality with contact-analogous trajectories (Damböck, Weißgerber, Kienle, & Bengler, 2012) for example. The head-up display specifically superimposes scene-linked symbology (Foyle, McCann, & Shelden., 1995), which allows it to augment reality (Azuma, 1997).

The interaction design under consideration uses visual (static and contact-analog head-up display), auditory (sound), tactile, and kinesthetic (active steering wheel, active accelerator pedal, and brake) interfaces concurrently to facilitate such natural, multimodal interaction. The "information modality," "multimodality," and "augmented reality" design patterns are an extract of this work (in Baumann et al., 2014b).

Interaction design and visual user-interface elements. Norman's (1988) seven *fundamental design principles* (e.g., "feedback" following any cooperative action), Shneiderman and Plaisant's (2010) eight *golden rules of interface design* (e.g., forming an interaction sequence based on the "seclusion of tasks" rule), and Nielsen's (1993) ten *usability heuristics* (e.g., designing a holistic user interface based on heuristic “consistency”) for all automated and cooperative subsystems formed the interaction design’s guardrails. To improve awareness of modes on a semantic level, the user interface informs about “what,” explains “why,” projects “next” in space and time, and assigns “who” to vehicles (Koo et al., 2015; Sarter & Woods, 1995; Wiener, 1989; Zimmermann & Bengler, 2013). Augmented user-interface elements encode these chunks into shape, brightness, color, and animation. Transparent, white elements present information; blue spheres provide a learnable metaphor for cooperative activities (Liu et al., 2015); augmented arrows represent action suggestions (Lütteken, 2013); and static user interface clusters display status information and request cooperation (Lütteken et al., 2016).

Gamification. Gamification as “the use of game design elements in non-game contexts” (Deterding, Dixon, Khaled, & Nacke, 2011, p. 9), “game ingredients” (Byron & Read, 2009), and “game mechanics” (Zichermann & Cunningham, 2011) adjoined the interaction design to further challenge and motivate cooperative behavior. Game design elements employed included time pressure, communication of cost and benefit, feedback of achievements, social cues, and point systems (Lütteken et al., 2016). These resulted in *social status* and *trade-off* game concepts as described in Zimmermann et al. (2018).

Big picture: the cooperative interaction design

Fig. 2.1 depicts the final cooperative lane-change assistant (in its main features consistent across iterations). It incorporates an augmented-reality user-interface design into the contact-analog head-up display. Cooperation occurs in the above-mentioned five phases (see fig. 2.1, blue arrow).

User involvement during cooperative requests. The automation system of the right-lane vehicle, $\mathrm{V_R}$ ($v = 33\,\mathrm{m/s}$), causes it to approach the slower truck, O ($v = 22\,\mathrm{m/s}$), which is tracked by a white bracket, (1). If $\mathrm{V_R}$ detects a potential cooperator, it uses an auditory action trigger and a pulsating semicircle, (2), to indicate commencement of the cooperative request phase. An augmentation in the rearview mirror uses a blue sphere, (3), to highlight the eligible cooperator, $\mathrm{V_L}$ ($v = 36\,\mathrm{m/s}$). $\mathrm{V_L}$ receives $\mathrm{V_R}$’s request in the form of the same sphere, (4), and the options to accept, (5), or reject, (6), via corresponding paddles on the steering wheel (or via the brake in Zimmermann et al., 2014). A closing circle, (7), symbolizes the remaining decision time. In addition, motivational game concepts provide decision support during the request (see Zimmermann et al., 2018).

A common course of action during cooperative maneuvering. The suggest preparation phase begins once the left-lane vehicle's driver accepts. The cooperation status adheres to the now-completed circle, (8), which is visible in $\mathrm{V_R}$. An arrow, (9), asks $\mathrm{V_L}$ to "open a gap." $\mathrm{V_L}$'s driver can tap the brake to consent. In the next phase, $\mathrm{V_L}$'s automation brakes gently ($a = -3\,\mathrm{m/s^2}$) to prepare the gap. A carpet representing the emerging gap is projected onto the street and is visible to both drivers, (10) and (11).

Blue-augmented arrows, (12), herald the suggest action phase once the carpet is next to $\mathrm{V_R}$. Those arrows suggest the time frame for a safe lane change. The right-lane driver steers left to accept the gap. The automation performs the lane-change maneuver in the concluding action phase. Cooperation is completed when $\mathrm{V_R}$ overtakes the truck.

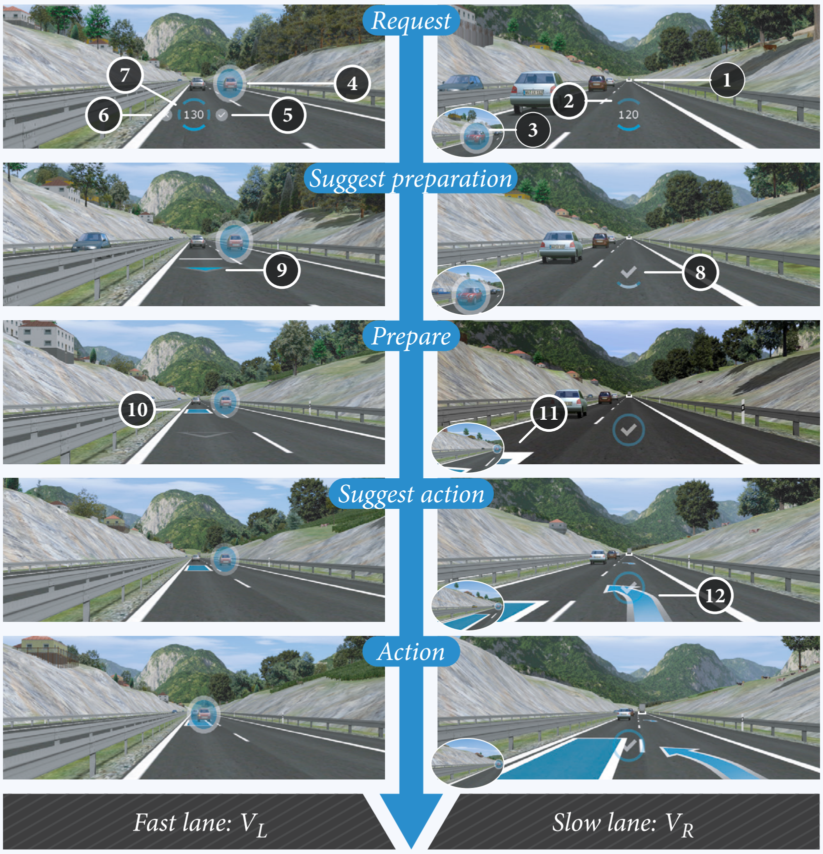

Figure 2.1: To support lane changes, the cooperative lane-change assistant (cLCA) offers augmented-reality user-interface elements in both lanes: leading vehicle (1), circle of cooperation (2, 8) with timer (7), cooperator in sphere (3, 4), request to accept (5) or reject (6) cooperation, brake arrow (9), carpet (10, 11), and lane-change arrow (12).

2.3 Implementation

The goal at this implementation stage is to excite the interaction designs (from chapter 2.2) in a driving simulator. Users require such a high-fidelity implementation to immerse themselves in cooperation, to experience it in the context of realistic driving situations, to form mental models of cooperation, and ultimately to assess its usefulness. This simulated level of fidelity is compelling for evaluating the interaction designs' efficacy (in reference to the research questions, see chapter 1.4)—since it matters "what users do, not what they say" (Nielsen, 2001). At the same time, a simulator implementation provides a good cost-value ratio and level of experimental control in contrast to a real-vehicle implementation.

Scripted scenarios. The lane-change scenario translated into driving situations in the human-in-the-loop simulator at the Technical University of Munich's Chair of Ergonomics. Other than Kelsch et al. (2015)—they used connected driving simulators within the scope of D3CoS—the simulations segmented the situation into a left-lane and right-lane perspective. One human driver repetitively drove both perspectives, each with simulated, scripted cooperation partners. Two considerations prejudiced this decision: Technologically, the SILAB driving simulation platform didn't support connected driving at that time. Methodologically, connected drivers would have provoked uncontrollable situations, much like those in a naturalistic driving study: how to ensure that $\mathrm{V_L}$, $\mathrm{V_R}$, and O meet repetitively in the same environment?

Scenario coordination and repeatability. SILAB has another constraint: simulated traffic can either be coordinated and influenced at predetermined milestones along the track (so-called "flowpoints") or triggered by—not more than ten—one-time, external events. Since the cooperative maneuver's implementation occupied the latter events (such as open gap, hold gap, and change lane), it also forced scripting of the simulated vehicles' coordination by predestining their time, location, and behavior during the lane change. This in turn implied that one cooperative situation lasting 30 s would require 3–4 more minutes of overhead for situation set-up and teardown. Constrained by these considerations, the experiments in Zimmermann et al. (2014) and Zimmermann et al. (2015) had only one situation repetition per scenario. Otherwise, situations would have taken too long and would have been predictable for the drivers.

Zimmermann et al. (2018) used swift interleaving of situations within modules, optimization of external events, and a custom-built, fuzzy-scenario-generation PHP script to improve repeatability. This maxed out the number of possible situation repetitions at 18, with a tolerable 90 s scenario duration including overhead.

Automation mitigates the challenge of coordination. Zimmermann et al. (2014) and Zimmermann et al. (2018) implemented two generations of cooperative driving automation from scratch as a C++ plugin for SILAB. Automation solved two problems. First, due to the inflexible scenario instantiation, a driver controlling the vehicle's speed flexibly could have missed the simulated cooperation partner; although the TTB calculation would have allowed this to certain extent (Bauer, 2013; Hochwieser, 2015). Deploying driving automation mitigated this coordination issue. Second, the investigation of shared authority and shared control in cooperative situations required a common course of maneuvers, which automation provided.

Kienle's (2014) and Cramer's (2015) cooperative automations inspired the implementation of "guide-o-mation" (the second-generation automation in Zimmermann et al., 2018). Simulated sensors detected road topology and traffic. The automation operated its vehicle on three levels: maneuver execution, trajectory planning, and longitudinal and lateral guidance. It coordinated basic maneuvers such as "free cruise," "follow," "open gap," and "change lane." It used Bézier curves to plan lateral and longitudinal trajectories. Proportional–integral–derivative (PID) velocity, emergency distance, and steering-wheel-angle controllers guided the brake, active accelerator pedal, and active steering wheel.

The implementation featured hands free, driver's eyes off the road, highly automated driving (according to SAE International, 2016) for free cruising and car following. However, it required user interaction for the *shared authority* maneuvers "open gap" and "change lane" (i.e., roughly conditional automation; SAE International, 2016). A cooperative *shared control* (Abbink et al., 2012; Flemisch et al., 2014; Sheridan & Verplank, 1978) allowed the driver to intervene at any time—by correcting rather than disengaging the automated system.

State automata for further coordination of interaction. Finite-state automata emerged as a valuable implementation method due to their small footprint; formal structure; and outstanding behavioral traceability, testability, and verifiability (Hopcroft, Motwani, & Ullman, 2013). The automation's maneuver controller profited from state automata, where for example the "steering" event caused a "keep lane" to "change lane" state transition, entailing a replanned trajectory. Likewise, the interaction sequence's five dedicated phases and transitions predestined the cooperative interaction's controller to be a state automaton. Discrete state automata are superior in maneuvering and automation modes whereas continuous algorithms (cf. Cramer, 2015; Kienle, 2014) adapt better to shared vehicle control.

The cooperative-interaction plugin checked the scenario triggers (i.e., when to start cooperation), user interaction (steering, braking, accelerating, or pressing the steering-wheel paddles) and state transitions (see table 2.1) against TTB to coordinate the interaction phases. More details on the calculations are presented in students' thesis (Bauer, 2013; Hochwieser, 2015).

User-interface plugins, such as the cooperative-interface control (Zimmermann et al., 2014) or the motivational user-interface controls (Weiß, 2015; Zimmermann et al., 2018), depended on the phase state. Those calculated elements' locations and tracked depot values such as mileage, time, points, or social status. The automation integrated the phase state into the haptic profile, for instance by reducing clockwise torque during "change lane" toward the left.

User interface graphics. All those coordinating plugins piloted their corresponding graphical OpenGL objects. The cooperative-interface control mapped visuals such as spheres, carpets, arrows, and status icons. The motivational user-interface controls rendered their respective request clusters, color status, time/point conditions, and depots. Vertex shaders and Bézier interpolations powered animations such as bending carpets, color shifts, fading objects, and tweening paths.

Experimental high-fidelity prototype in real vehicles. A secondary, experimental narrative should be mentioned here. The cooperative-interaction concept was implemented for real vehicles with the objective of testing its technical feasibility and exploring its transferability to the road. Three standard, manual cars carried tablet computers and a web service exposed the state automaton and its TTB calculations on a web server in PHP. The latter gathered GPS coordinates via cellular 3G network from the tablets and conducted the vehicles via speed suggestions into a suitable starting position as V_L, V_R, or O on the highway (A9 in Germany, between Garching and Ingolstadt). HTML5 birds-eye-view representations of the cooperative lane-change assistant suggested the "brake" or "change lane" actions to the drivers after a flying start. A few *guerrilla HCI* tests with the prototypical implementation revealed that although the coordination appeared to be robust, poor network quality, mental mapping, or human attentional issues frequently caused cooperation to fail. Hochwieser's (2015) student thesis describes the project.

Big picture: high-fidelity prototypes in the driving simulator

The outcome is a ridable prototype in the driving simulator featuring functional coordination and interaction. Although the implementations are comparable across iterations, they incorporate different generations and features tailored for the experiment. Videos present the implemented cooperative and motivational interaction.

- The 2013 interaction concept (https://youtu.be/XB3Q_gfyK44) in Zimmermann et al. (2014) and Zimmermann et al. (2015)
- The 2015 trade-off interaction concept (https://youtu.be/LTudBOEWinM) in Lütteken et al. (2016) and Zimmermann et al. (2018).
- The 2015 social-status interaction concept (https://youtu.be/mG29qhtkTiM) in Zimmermann et al. (2018).

2.4 Evaluation

This stage evaluates cooperative interaction, subjective perception of cooperation, and motivation of cooperation with the ultimate goal of answering the research questions (see chapter 1.4). Their answers, with a focus on human-machine interaction within cars on the one hand and on social interaction between drivers on the other, require human-in-the-loop experiments. Hence, test participants evaluate the implemented cooperative interaction (from chapter 2.3) in the driving simulator.

Three research questions—three studies. Table 2.2 operationalizes the three groups of research questions into experiments, their participants, factors, and variables. All experiments used repeated measures designs to provide drivers with 8 to 54 cooperative situations from both left-lane (opening a gap) and right-lane (changing lanes) perspectives. One participant at a time drove the cooperative interaction concepts repetitively.

Table 2.2: The driving-simulator experiments at a glance.

Research question	Experiments	Participants (situations)	Factors	Variables
Interaction	Zimmermann et al. (2014)	25 (10)	2 perspectives × 2 concepts (timing, workload)	success rates, distances, phase durations, gaze
Perception	Zimmermann et al. (2015)	10 (8)	2 perspectives × 3 situations (timing, success)	situational scores
Motivation	Lütteken et al. (2016); Zimmermann et al. (2018)	39 (54)	2 perspectives × 4 concepts × 6/9 repetitions (behavior, cost/benefit ratios, timeliness)	acceptance rates, phase durations, concept scores

Zimmermann et al. (2014) contrasted no cooperative support against the cooperative interaction concept under different timings and workload conditions, and evaluated it regarding success, safety, and timing. Zimmermann et al. (2015) tested the users' subjective perception of different cooperative situations. Lütteken et al. (2016) and Zimmermann et al. (2018) evaluated the cooperative interaction concept against three motivational ones regarding acceptance, timing, and behavior.

Experimental gaze metrics. Since the visual channel is the remaining interaction modality during highly automated driving (according to SAE International, 2016), reading the driver visually is a promising approach to assessing the driver's state in the intention layer of cooperative interaction (Bengler et al., 2012). Hence, gaze metrics gathered by eye tracking were a side aspect of the experiment in Zimmermann et al. (2014), elaborated in Rothkirch's (2013) student thesis, and resulting in the "visual workload" design pattern (in Baumann et al., 2014b).

Questionnaires for subjective metrics. Two newly developed questionnaires contributed to subjective metrics. A situational questionnaire captured the subjectively perceived value of cooperation with a score based on satisfaction, relaxation, accordance, and trust (Zimmermann et al., 2015). A concept questionnaire captured cognitive and behavioral processes of change with a score based on nine items, such as consciousness raising or self-liberation (Zimmermann et al., 2018). All items were rated on bi-polar scales in online forms during the driving simulations.

Acceptance rates, safety, and phase durations as objective metrics. In all of the experiments, drivers could choose to cooperate by accepting requests. Hence success rates, the share of successful cooperations per situation (in Zimmermann et al., 2014), and acceptance rates, the share of "accept" decisions per request (in Lütteken et al., 2016; Zimmermann et al., 2018) formed objective metrics. Although success is a stronger criterion than acceptance, left-lane rates are comparable across experiments (see Zimmermann et al., 2018).

Zimmermann et al. (2014) used vehicle distances (as safety metric) and phase durations (as interaction metrics depending on human decisions). Their combination didn't allow firm conclusions about safety or willingness to cooperate, due to the automation's limited maturity in the first iteration. Since the drivers anticipated and the automation prevented dangerous maneuvers, the safety question moved into the background. Zimmermann et al. (2018) used phase durations to investigate underlying decision conflicts and to assess the drivers' willingness to cooperate (Kahnemann, 2012).

Summative assessment by questionnaires and interviews. Summative questionnaires assessed (motivational) user-interface quality (in Zimmermann et al., 2014, 2018); situational questionnaires tied perception of cooperation to its reasons (in Zimmermann et al., 2015); and participants discussed the interaction and discovered sources of motivation during interviews (in Zimmermann et al., 2018).

Big picture: driving simulator experiments

Each iteration led to an experimental evaluation in the static driving simulator (see fig. 2.2) at the Chair of Ergonomics. Its virtually-all-around projection was important for both forward (left-lane) and rearward (right-lane) interaction during the lane-change scenario.

Figure 2.2: The driving-simulator setup with the cooperative interaction concepts under test. Photographers were Andreas Haslbeck (exterior, 2015) and Tobias Hase (interior, 2016).

3 Five papers on cooperative interaction

The papers composing this publication-based doctoral dissertation are summarized in the sequel.

3.1 A multimodal interaction concept for cooperative driving (Zimmermann & Bengler, 2013)

Zimmermann, M.[1], & Bengler, K. (2013). A multimodal interaction concept for cooperative driving. In *IEEE Intelligent Vehicles Symposium (IV)*[2] (pp. 1285–1290). Gold Cost, Australia: IEEE. doi: 10.1109/IVS.2013.6629643

Objective. Aim of this paper is to establish an interaction sequence and user-interface concept from theory for cooperative lane-change maneuvers.

Background. Based on Hoc's (2001) multi-agent definition of cooperation, this paper elaborates Bengler et al.'s (2012) levels of cooperation: intention, cooperation mode, allocation, and interface.

Method. The work forms a cooperative lane-change scenario involving two automated, connected vehicles. A process analysis of this scenario on all levels of cooperation establishes a cooperative-interaction concept.

Results. This results in activity and sequence models in UML covering the interaction semantics. The paper identifies what, why, next, and who information chunks (based on Sarter & Woods, 1995) to be important for cooperation and its modes. A multimodal interaction prototype and its augmented-reality user-interface elements conveys these chunks.

Conclusion. The paper sketches an interactive system to support the lane-change scenario subject to further research. It forms the theory-driven basis of the subsequent driving-simulator experiment in Zimmermann et al. (2014).

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[1] The author of the present dissertation wrote most of the paper; developed the research question; derived, analyzed, and modeled the cooperative interaction; and established the concept.

[2] The full paper was peer reviewed.

3.2 Acting together by mutual control (Zimmermann, Bauer, Lütteken, Rothkirch, & Bengler, 2014)

Zimmermann, M.[3], Bauer, S., Lütteken, N., Rothkirch, I. M., & Bengler, K. J. (2014). Acting together by mutual control: Evaluation of a multimodal interaction concept for cooperative driving. In W. W. Smari, G. C. Fox, & M. Nygård (Eds.), *2014 International Conference on Collaboration Technologies and Systems (CTS)*[4] (pp. 227–235). Minneapolis: IEEE. doi: 10.1109/CTS.2014.6867569

Objective. This driving-simulator study aims to design, implement, and evaluate the interaction concept from Zimmermann and Bengler (2013). The paper reports a driving-simulator study and analyzes the interaction's quality and timing. It also investigates the effect of workload on different gaze metrics.

Interaction design. The paper's first part operationalizes the lane-change scenario concerning traffic cooperation, human-machine cooperation, and automated driving. It constrains the interaction model (from Zimmermann & Bengler, 2013) with a cooperation time adding up to 23 s. In line with the D3CoS design patterns (Baumann et al., 2014b), the work designs the multimodal user interface and implements it in the driving simulator.

Method. Twenty-five participants drove left-lane and right-lane situations repetitively in the experiment. A within-participants design embeds the factors concept, timing, and workload: with and without the cooperative system, 20 s and 30 s interaction time, and under light, medium, or heavy workload. Besides the cooperation (success rate) and safety (distance) outcomes, an eye-tracker recorded different glance metrics.

Results. The interaction concept significantly increased cooperation in left-lane situations, when offering gaps to other drivers (from 36 % to 88 %). When requesting such gaps for own lane changes in the right-lane situation, the interaction was unable to significantly improve cooperation (88 % versus 100 %). A total interaction time of 30 s was sufficient, whereas 20 s was too brief in the left lane. The cooperative lane change was safer, as the automation prevented hazardous maneuvers. The experiment found evidence that induced workload influences gaze metrics such as pupil diameter and saccade rate, as well as steering latency.

Discussion. Drivers are more cooperative with the interaction concept. The user-interface elements for action suggestion, carpets, and arrows, are generally perceived well. The paper identifies the need to diversify the scenario (in Zimmermann et al., 2015) and to design for drivers' motivation for cooperation (in Lütteken et al., 2016; Zimmermann et al., 2018).

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[3] The author of the present dissertation wrote most of the paper, developed the research questions, designed the driving-simulator experiment, implemented the automation, supervised the co-authors' implementation of the scenario and interaction, and conducted an independent statistical data analysis.

[4] The full paper was peer reviewed.

3.3 A Roland for an Oliver (Zimmermann, Fahrmeier, & Bengler, 2015)

Zimmermann, M.[5], Fahrmeier, L., & Bengler, K. J. (2015). A Roland for an Oliver? Subjective Perception of Cooperation During Conditionally Automated Driving. In W. W. Smari, W. N. McQuay, & M. Nygård (Eds.), *2015 International Conference on Collaboration Technologies and Systems (CTS)*[6] (pp. 57–63). Atlanta: IEEE. doi: 10.1109/CTS.2015.7210400

Objective. This driving-simulator study is inspired by the question about whether driving—involving unequal characters and capabilities, and resulting in conflicts—is a quid pro quo. This is based on the left-/right-lane asymmetry observed in Zimmermann et al. (2014). The paper investigates subjective perception of lane-change cooperation.

Questionnaire design. The work identified trust, confidence, and control as important for human perception of cooperation (Das & Teng, 1998; McKnight & Chervany, 2001). Transfer from cooperation questionnaires (Dalton & Cosier, 1989; Deutsch, 1949), which are not applicable for driving scenarios, results in a 12-item questionnaire matching the dimensions satisfaction, relaxation, accordance, and trust on a 6-point semantic-differential scale.

Method. Ten participants drove eight left-lane and right-lane situations in the driving simulator. The work modifies the optimal 30 s scenario (from Zimmermann et al., 2014) regarding the factors success and timing. Participants completed the questionnaire after each situation, resulting in a sample of 80 dependent situations.

Results. Participants generally rated the optimal situations more positively. They valued successful cooperation significantly over uncooperative situations. The ratings support the asymmetry: cooperation is perceived to be more beneficial when driving in the right lane. Modified situations appear to be significantly less trustworthy than optimal ones. A factor analysis reveals two factors: extrinsic and intrinsic contribution to cooperation. Drivers value successful cooperation, but attribute failure to the cooperator.

Discussion. The work confirms the left/right-lane asymmetry. However, even in the left lane, drivers perceive successful cooperation positively. They learn and value the benefits of cooperative interaction support. The questionnaire has shown a high reliability and is therefore a suitable measurement method for assessing cooperation. However, the study pointed out the need for motivational support, since (good and poor) coordination is not always understandable for human drivers.

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[5] The author of the present dissertation wrote most of the paper, developed the research question, designed the driving-simulator experiment, supervised the co-author's scenario implementation, updated the automation, supervised and contributed to questionnaire design, and conducted an independent statistical data analysis.

[6] The full paper was peer reviewed.

3.4 Using gamification to motivate human cooperation… (Lütteken, Zimmermann, & Bengler, 2016)

Lütteken, N.[7], Zimmermann, M.[7][8], & Bengler, K. (2016). Using Gamification to Motivate Human Cooperation in a Lane-change Scenario. In *2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC)*[9]. Rio de Janeiro, Brazil: IEEE. doi: 10.1109/ITSC.2016.7795662

Objective. Aim of this driving-simulator study is to investigate a decreasing acceptance of cooperative maneuvers under time pressure, compared to the 88 % from Zimmermann et al. (2014). To motivate lane-change cooperation under time pressure, the study uses "game design elements in non-game contexts" (Deterding et al., 2011, p. 10), a technique known as gamification. A driving-simulator experiment tests the resulting interaction concept.

Game design. Based on Byron and Read's (2009) "game ingredients" and Zichermann and Cunningham's (2011) "game mechanics," the paper sketches a redeemable-point system for lane changes. Drivers in the right lane pay credits to advance; left-lane drivers receive credits in exchange for their time. A simulation of the model validates the point system's effectiveness, and a visual interface moderates the trade-off.

Method. Thirty-nine participants drove 18 trade-off situations repetitively in the driving simulator (within the scope of Zimmermann et al., 2018). The concept factor quantifies the raw lane change (from Zimmermann et al., 2014) versus the gamified trade-off version. The time/point ratio factor is used to investigate cheap, medium, and expensive trade-offs. The experiment measures acceptance rates and reaction times.

Results. Acceptance rates decrease to 67 % under time pressure in the left lane. Using the motivational trade-off increases left-lane acceptance of cooperation to 87 %. Drivers in the right lane waive cooperative maneuvers (64 %), since those are not gratis. They furthermore identify good (cheap or expensive) deals.

Discussion. More realistic driving scenarios (e.g., those under time pressure) show the need to motivate cooperation. Gamification of user interfaces links the costs and benefits of cooperation. Traffic coordination could exploit such concepts to optimize performance and improve subjective perception of cooperation at the same time.

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[7] Joint first authors.

[8] The author of the present dissertation dissertation contributed equally to writing the paper, developed the core research question, designed the driving-simulator experiment, managed the project, supervised the co-author's implementation of the social interaction, re-implemented the automation, contributed to updating the interaction controller, supervised the experiment, took charge of some experimental sessions in the driving simulator, and conducted an independent statistical data analysis.

[9] The full paper was peer reviewed.

3.5 Carrot and stick: a game-theoretic approach… (Zimmermann et al., 2018)

Zimmermann, M.[10], Schopf, D., Lütteken, N., Liu, Z., Storost, K., Baumann, M., Happee, R., Bengler, K. J. (2018). Carrot and stick: A game-theoretic approach to motivate cooperative driving through social interaction. *Transportation Research Part C: Emerging Technologies*[11], *88*, 159–175. doi: 10.1016/j.trc.2018.01.017

Objective. This driving simulator study aims to compare different approaches to motivating cooperative maneuvers under time pressure. It exploits game-theory to motivate cooperation by applying rewards and sanctions in both resulting interaction concepts.

Game theory and design. The game-theoretic model reveals that rational left-lane drivers would behave less cooperatively under time pressure. It identifies a social dilemma (Messick & Brewer, 1983) mitigated by indirect reciprocity (Nowak & Roch, 2007). The paper sketches two responses to the social dilemma: a social-status game and a trade-off game, each intended to rebalance unequal lane-change incentives. Different interaction designs power the games.

Method. Thirty-nine participants drove a total of 2086 lane-change situations under time pressure in the driving simulator. The mixed-design study involves the factors concept (baseline, two social-status concepts, and trade-off), timeliness (late and on time), foreign acceptance of cooperation, and foreign status. The experiment measures acceptance rates and reaction times.

Results. Time pressure effectively restrained cooperation. Drivers behaved indirectly reciprocally to group behavior; additional social information facilitated direct reciprocity. Both game concepts effect motivation under time pressure: revealed social status results in fairer driving through rewards and sanctions, and the trade-off interaction makes cooperation a strategic game.

Discussion. When it comes to cooperative, social interaction, carrots and sticks influence drivers for the better, shaping their behavior even under time pressure. Such concepts ought to have a beneficial effect on traffic performance and on the subjective acceptance of its coordination, thus strengthening maneuver-based cooperation.

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[10] The author of the present dissertation wrote large parts of the article, developed the core research questions, designed the driving-simulator experiment, managed the project, supervised the co-authors' implementation of the social interaction, re-implemented the automation, contributed to updating the interaction controller, supervised the experiment, took charge of some experimental sessions in the driving simulator, and conducted an independent statistical data analysis.

[11] The manuscript was peer reviewed.

4 Nailing the research goal

This doctoral dissertation, which is based on the highway lane-change scenario, acquires cooperative interaction, explores its subjective perception, and finally motivates cooperative behavior. These results are summarized below and discussed from both joint perspectives: human-machine cooperation and traffic cooperation.

4.1 Cooperative interaction

The interaction design proposed in Zimmermann and Bengler (2013) serves as a proof of concept for cooperative lane-change support. Initial evaluation in the first driving-simulator study in Zimmermann et al. (2014) demonstrates the design's effectiveness for improving cooperation. The augmented-reality user interface appears suitable to herald cooperation (what), highlight cooperators (who), communicate cooperation's necessity (why), and suggest understandable actions (next). The cooperative lane changes are safe if the driving-automation prevents hazardous maneuvers (Zimmermann et al., 2014).

If a gap is available, the cooperative system offers qualified support to drivers approaching a truck in the right lane. Right-lane drivers have ample time to recognize the obstacle in their lane, anticipate a gap early enough to deal with it, and cash in on the opportunity. The problem—a vehicle rear-ending a truck—is obvious from the right-lane perspective. The cooperative system is nevertheless advantageous when requesting a gap (Zimmermann et al., 2014).

The design drastically improves cooperation. Left-lane drivers can open gaps for vehicles trapped in the slow lane because the interaction effectively informs them about the right-lane driver's need. Since the designers of the first driving-simulator study ensured the drivers' cooperation by instructing them to "be cooperative," the cooperative system had opportunities to support the ability to detect cooperative situations, communicate, and cooperate by exposing knowledge about problems and suggesting solutions (Zimmermann et al., 2014).

Such improvement comes at a cost though: it requires an overall interaction time of 30 seconds, starting with the request for the fast-lane driver to anticipate the upcoming lane change. This is a long anticipation horizon for both humans and technology; but this duration is adequate and necessary to involve users, let them agree on cooperation, and facilitate their ability to cooperate.

4.2 Subjective perception of cooperation

The imbalance between left-lane and right-lane drivers' incentives brings us to the second crux: the lane-change situation harbors an asymmetric give and take where one driver's gain (e.g., the right-lane driver's time) entails other drivers' losses (e.g., the left-lane drivers' perceived comfort reduction). The implementers of the second driving-simulator study, documented in Zimmermann et al. (2015), gathered drivers' subjective perceptions of cooperation in situations varying by success and timing.

The perception questionnaire elicits information about satisfaction, relaxation, accordance, and trust. Its creators seek content validity using a literature review, criterion validity via six planned situations, and factorial validity with a factor analysis. The associated experiment identified two hidden factors: drivers' extrinsic and intrinsic contributions to cooperation. The factors appeared to be reliable along the way, so the questionnaire now constitutes a new metric for assessing cooperative driving maneuvers (Zimmermann et al., 2015).

Drivers perceive lane changes more cooperatively when the associated maneuvers succeed or when they're driving in the right lane. The extrinsic and intrinsic perspectives account for drivers concluding that it is someone else's fault—and problem—when cooperation goes poorly from their perspective. However if coordinated properly, drivers learn and value the benefit of cooperative-interaction support. The cooperative-interaction concept brings them subjectively closer to eye level. Asymmetry notwithstanding, drivers in the left lane perceive successful cooperation positively, taking their time loss in stride (Zimmermann et al., 2015).

All this entails imperatives for human acceptance of future automated vehicles. First, they need to inform drivers about the rationale behind maneuvers. Second, drivers' subjective perception of cooperation has to be part of maneuver cost and utility. Third, automated vehicles should react better whenever cooperation is offered to or requested from them. This implies that cooperators should stick to cooperative agreements once they're made. Subjective perception will obviate the notion that implicit, stochastic, on-board intent prediction can facilitate efficient cooperation. Cooperation will instead require explicit interaction and agreements made through V2V communication.

4.3 Motivation of cooperation

Knowing about the drivers' positive perception of cooperation and the interaction concept's ability to support cooperation, the third driving simulator study instructs drivers to be "in time." Lütteken et al. (2016) and Zimmermann et al. (2018) thereby challenge their motivation to cooperate.

Time pressure discourages drivers from opening gaps; they act less cooperatively in the lane-change scenario. We also observe rational, egocentric behavior like this on the road.

Optimization of individual advancement in the left lane creates a social dilemma with poorer outcomes for drivers in the right lane. Indirect reciprocity mitigates the dilemma: drivers cooperate more often in cooperative than in uncooperative environments (Zimmermann et al., 2018).

Introduction of the social-information concept allows drivers' prior cooperation-related behavior to be revealed. This facilitates direct reciprocity by reliably punishing previously uncooperative drivers with less future cooperation than that accorded to previously cooperative ones. The game mechanic of reward and sanction produces a motivational effect: drivers are generally most cooperative when trying to maintain their good reputation. Social information about past behavior represents a fairer, more objective criterion for cooperation than do, for instance, car brand, horsepower, or gender (Zimmermann et al., 2018).

The novel trade-off concept recasts driving as a strategic game during which drivers can barter their time for credits. It motivates left-lane drivers to accept disadvantageous maneuvers so that they can later exchange the points earned for cooperation when they need it. Drivers prefer cheap conditions to expensive deals, which primes behavior. This mechanism encourages drivers in the right lane to behave more altruistically by not hindering others (Lütteken et al., 2016).

Traffic performance will inevitably depend on drivers' willingness to cooperate. Thus, future vehicles will need to involve their drivers in cooperative maneuvers; and their designers will have to motivate, challenge, and prime drivers (Lütteken et al., 2016). It's the combination of "carrots" and "sticks" that will make driving fairer (Zimmermann et al., 2018).

4.4 Human-machine cooperation, or involving the driver of automated cars

The proposed interaction concepts allow for information exchange between humans and machines, thereby necessitating a common frame of reference (Hoc et al., 2009) and suggesting more natural interaction (Norman, 1990). "Semi-automatic," cooperative lane changes justified by arguments for safety and cooperation should involve the driver from the start. Requesting cooperation is important for securing the driver's recognition of the impending maneuver's necessity and acquiescence during its execution. Automated systems will act conservatively because merging is dangerous, especially in dense, complex situations. They will hew to the normative model whereas human drivers will likely bend the rules. Another *irony* will manifest itself during automated driving: drivers do not intervene when they should—and vice versa, which weakens the intended coordination. On the one hand, empirical evidence suggests that drivers are disinclined to regain control to change lanes (Jamson, Merat, Carsten, & Lai, 2013), and it's more dangerous when they do (Hoedemaeker & Brookhuis, 1998). On the other hand, drivers tend to assume manual control in anticipation of other traffic participants' lane-change maneuvers (Minderhoud, 1999).

From an automated-systems perspective, human-machine cooperation could mitigate out-of-the-loop problems. Since the driver is involved, he or she has already perceived, analyzed and decided to execute the maneuver (Parasuraman, Sheridan, & Wickens, 2000). This brings the now-activated human closer to the loop and prepares for potential takeovers. He or she no longer "drives," but rather "plays driving" challenged through gameful interaction. This provides great potential for keeping the driver alert to and engaged in strategic, maneuver-based control. Zimmermann et al. (2018) have demonstrated this experimentally.

4.5 Traffic cooperation, or the social context of maneuvers

Humans will be integrated into whatever traffic-performance optimizations superordinate traffic coordination implements. Social norms and contexts (Rakotonirainy et al., 2014), and personal, socio-emotional, and systemic motivators (Benmimoun et al., 2004) already influence the character of cooperation on the road, just as drivers' cognitive, modulating, and motivational states do (Wilde, 1976). Time pressure and perceived fairness are among these factors (Zimmermann et al., 2018). Hence, intelligent traffic coordination (cf. Najm et al., 2010; Wang et al., 2015) has to take them into account.

In turn, the interaction and user-interface concepts discussed in this dissertation are waiting in the wings to communicate complex optimization, such as traffic flow, and to support social cooperation via simple surrogate explanations such as credits. Concerning credits, *reasonable* cooperation has to cost the beneficiary less than noncooperation does and pay off for the benefactor. Such game mechanics allow cooperation to be enforced and primed, and they ultimately resolve the social dilemma. Lütteken et al. (2016) and Zimmermann et al. (2018) have demonstrated that this will simultaneously engage drivers and accommodate their normative model.

5 Ten design recommendations for cooperative systems…

The following ten design recommendations are lessons learned from the previously described experiments and deduced from human behavior and working design. The following dimensions are taken into account when classifying general rules applicable across domains for designing cooperative systems. Hoc et al. (2009) decompose cooperative activities into three levels *meta*, *plan*, and *action*, modeled in order of long- to short-term cooperation. This corresponds broadly to driving modes at the *strategic* planning, *tactical* maneuvering, and *operational* control levels (Donges, 1982; Hoc et al., 2009; Michon, 1985; Ranney, 1994). The respective time scales range from hours for strategies to milliseconds for sensorimotor control. Küster and Reiter (1987) identify *will*, *knowledge*, and *ability* layers being as important for interacting with drivers. Since these categories appear to be isomorphic, they will constitute the classification's first dimension.

Information chunks for cooperative systems form the classification's second dimension. These are *what* (actions and status), *why* (explanations), and *next* (time and space) following Wiener (1989) and Sarter and Woods (1995), and complementing the *who* (responsibility and cooperator) aspect in Zimmermann and Bengler (2013). Table 5.1 relates both dimensions to classify the design recommendations for cooperative systems.

Table 5.1: Ten design recommendations for cooperative systems.

	Action **Operational** **Ability**	**Plan** **Tactic** **Knowledge**	**Meta** **Strategic** **Willingness**
What	Furnish status!	Sequester phases!	
Why	Recapitulate decisions!	Justify necessity!	Reward and sanction!
Who	Involve users!	Address explicitly!	Interact socially!
Next	Suggest actions!	Anticipate actions!	

5.1 …at the operational *action* level

Users are in the thick of cooperative situations at the action level. For instance, they need to decide whether or not to cooperate based on given criteria, or they have to act—for example, by braking for a cooperation partner. Cooperative action happens on the "anticipative control" timescale, which Tanida and Pöppel (2006) determine to be 3 seconds. Interaction and user-interface concepts at the action level improve the users' ability to react and orient themselves during cooperation.

Furnish the status of cooperation! Inform the drivers about the status of cooperation and its current progress with notifications such as "Lane is changed." or "Gap is opened." and link visual cues to the scenery (Zimmermann et al., 2014). Doing so diminishes the incidence of erroneous user intervention, gives feedback (Norman, 1990), and supports a common frame of reference (Hoc, 2001).

Recapitulate cooperators' decisions! Recapitulate one's own and the human or machine cooperators' decisions during asymmetric cooperation. Once there is cooperative accordance, design the interaction to remind about, support, and enforce it multi-modally, for instance, by making it visually sticky, or sending haptic feedback (Zimmermann et al., 2014, 2018). Consent or accordance is perceived as well-coordinated and thus cooperative (Zimmermann et al., 2015). Allegorize the individual or group benefit during cooperation to promote consent (Lütteken et al., 2016; Zimmermann et al., 2018).

Involve users into cooperative decisions! Involve the users in the decision process, because being in control is important for both cooperation (Zimmermann et al., 2015) and automation (Banks & Stanton, 2016). Let the users decide, since doing so motivates them to stick to the chosen actions and makes the decision available to the automation and other drivers ("certainty of tasks and goals" in Baumann et al., 2014b). Apply Hoc et al.'s (2009) *mutual control* principle to allay arbitration and decision conflicts (Zimmermann et al., 2014).

Suggest cooperative actions! Suggest the optimal action or action alternatives and project future effects by linking actions to their spatial and temporal outcomes using means such as scene-linked carpets and arrows. This is important, because algorithms optimize cooperative multi-agent behavior such as traffic-flow control better than humans do, but the outcomes are too complex for humans to understand at the operational level (Zimmermann et al., 2014; "action suggestion user interface" in Baumann et al., 2014b).

5.2 …at the tactical *plan* level

Users form a tactical understanding of a situation, such as needing to prepare for a lane change, on the plan level. Such maneuvering happens in a matter of seconds according to Michon (1985), with a typical anticipatory horizon of 10 s (Popiv, Rakic, Bengler, Bubb, & Nestler, 2009). Users benefit from interaction concepts that support a prior knowledge of a situation and thus establish a frame of reference.

Sequester cooperative phases! Segment the cooperation process into secluded activities, which form interaction phases. Make them distinctive, understandable, and yield closure (Shneiderman & Plaisant, 2010). Sequence the cooperative activity into initiation, maintenance, and completion (Kelsch et al., 2015). Conduct a task analysis and derive a scenario-dependent interaction (e.g. request, …, action; Zimmermann & Bengler, 2013). If the available time budget is tight, define safe states such as abort for failed cooperation and retry later with a different cooperation partner (Zimmermann et al., 2014).

Justify necessity of cooperation! Highlight the situation requiring cooperation, such as the presence of an obstacle, and its criticality (e.g., an accident hazard) to justify the need for cooperation. Humans tend to cooperate (Zimmermann et al., 2014), value the benefits and contributions of cooperation (even from the endowing perspective; Zimmermann et al., 2015), and behave with reciprocal altruism (Zimmermann et al., 2018) when they apprehend a need. Consider using surrogate interpretations such as virtual credits (Lütteken et al., 2016) to reduce complexity. Explanations of why cooperation is advantageous will generally improve satisfaction, promote relaxation, and strengthen accordance and trust thereby facilitating its acceptance (Zimmermann et al., 2015).

Address cooperators explicitly! Address the cooperator explicitly ("explicit addressing" in Baumann et al., 2014b) when requesting cooperation (i.e., help) and thereby avoid diffusion of responsibility (Latané & Darley, 1970). Team up only two cooperators at a time. Small groups promote cooperation better than large ones (Kollock, 1998); they're cognitively manageable, and easily understood. Link dyads of cooperators through a suitable interface (Kelsch et al., 2015). Direct the information between cooperators and avoid multiple simultaneous flows ("directed information" in Baumann et al., 2014b; Kelsch et al., 2015; Zimmermann et al., 2015, 2018).

Anticipate cooperative actions! Initiate cooperation as late as possible to make the situation technologically manageable and reliably resolvable. However, initiate it as soon as necessary to be cognitively manageable for the human user to anticipate cooperation. A time budget of 5 seconds is insufficient for information acquisition and analysis (at the plan level), a subsequent decision, and action implementation (at the action level). Even 7 seconds is tight for the use-case takeover from automation (Gold et al., 2013). Four to six seconds is just right for analyzing and deciding about upcoming lane-change scenarios *if the decision* comes with explicit addressing, surrogate justifications, and action suggestions (see above), and *if the interaction* provides additional phases for the action implementation (Zimmermann et al., 2014, 2018).

5.3 …at the strategic *meta* level

Possible cooperators formulate their cooperation strategies, for instance, to maximize payoff, compensate drawbacks, or strive for fairness, at this level. The timescale for strategies is long term and ranges from minutes to days. The potential of interaction concepts is to influence willingness to engage in cooperative behavior based on a give-and-take to support users' goals.

Reward cooperation and sanction defection! Reward cooperators and sanction defectors to motivate cooperative strategies or maneuvers (Zimmermann et al., 2018). Do both. It's their combination that makes them effective (Zimmermann et al., 2018). Strive for *global* symmetry of cooperative systems to achieve fairness (e.g., design a zero-sum game and limit the possible "taking" to the amount of prior "giving"; Zimmermann et al., 2018). When situations are *locally* asymmetric (e.g., being in the left or in the right lane), support the user in building strategies and deciding by visualizing cost and benefit (e.g., regarding safety, performance, or comfort), since users create their mental models of cooperative interaction (Lütteken et al., 2016) based on subjective perception (Zimmermann et al., 2015). Support the mental model with a trade-off (Lütteken et al., 2016). Contrast cost in one domain (e.g., time) with achievable benefits in another (e.g., currency). Users will accept self-penalties if doing so compensates for asymmetry and supports future fairness (Lütteken et al., 2016; Zimmermann et al., 2018).

Let cooperators interact socially! Establish a link between cooperators to facilitate social interaction. Doing so will encourage them to build mental models incorporating fruitful cooperative strategies (Kelsch et al., 2015; Zimmermann et al., 2015). Embed them into a social context, establish group identity (Kollock, 1998), provide social cues (e.g., prior cooperation-related behavior; Rakotonirainy et al., 2014; Zimmermann et al., 2018), and allow them to interact strategically (e.g., bartering time for points; Lütteken et al., 2016).

6 Impact and outlook

Today's cooperation on roads is regulated by laws such as StVO (2013) and is personally, socially, or systemically motivated (Benmimoun et al., 2004). It is driven manually, subject to limited intent communication (i.e., poor user anticipation; Treat et al., 1979), individual decisions (i.e., poor efficiency; Zheng et al., 2013), and risky-action implementation (i.e., poor safety; Golob & Recker, 2004). Future automated systems promise connected communication implying increased technical anticipation, central coordination yielding high efficiency (Wang et al., 2015), and improved maneuvering, which enhances safety (Najm et al., 2010).

The long-term reality will lie in between due to low levels of automation attributable to the user's motivation or opportunity to intervene, and other drivers' interference due to shallow market penetration. Humans will remain a pivotal (personal, social, and systemic) factor in cooperation under this assumption. Intent communication and individual decisions remain problematic at both the manual and automated extremes.

Hence, this dissertation implements a *user-centered process* to strive for cooperation and proposes *cooperative interaction concepts* to improve it within cars (human-machine cooperation) and between drivers (traffic cooperation). A novel approach to design cooperation, models of cooperation, an interaction design for cooperation, knowledge of subjective perception of cooperation, and techniques to motivate cooperation are the unique results of this research, which culminates in *design recommendations*. Following these recommendations and their human-centric perspective will ultimately enable improved driving safety, optimize traffic flow, and enhance driver comfort.

The road to cooperation

The user-centered design approach is integral to, and the only viable way of, improving cooperation. Design and implementation stages (usually exclusively industrial) are just as important as analysis and evaluation stages (usually exclusively academic) under this objective.

For research. Researching interactive and cooperative systems challenges empirical methods (cf. de Groot, 1969). It's no longer just about "observation" of cooperation and "deduction" of experiments, it requires the presence of tangible prototypes of cooperation instead.

Or, in the words of Scriven's (1967) metaphor[1]: if you want to evaluate an axe, you will have to make one first. Users need to experience cooperation to test its improvements, which in turn requires its design and implementation.

For development. Developing interactive and cooperative systems challenges their manufacturers in turn. Interaction and cooperation are subject by definition to mutual interference from users (now human and machine agents). Replacing "interaction" with strictly separate "responsibilities" and "capabilities" (SAE International, 2016), or equating "cooperation" with "connection" or "autonomy" is system-centric and constitutes a naive attempt to remove the human factor from consideration. Technical systems need to undergo empirical user tests, and analysis and evaluation is the answer.

For both worlds. User-centered design has proven its efficiency across iterations for both research and development (Lütteken et al., 2016; Zimmermann et al., 2014; Zimmermann & Bengler, 2013; Zimmermann et al., 2015, 2018). The use of two original methods illustrates this context. First, the formal interaction model, derived from an analysis of natural driving (Zimmermann & Bengler, 2013), allowed its one-to-one implementation in state automata (Zimmermann et al., 2018). Second, game theory was not just a method to analyze and coordinate cooperation (Altendorf & Flemisch, 2014; Hollander & Prashker, 2006; Wang et al., 2015; Zohdy & Rakha, 2012), but moreover a potent method to design its interaction (Zimmermann et al., 2018). Only the creative application of such methods results in high-quality interaction.

A long road, getting from here…

A multimodal, *cooperative interaction* concept is now available (Zimmermann & Bengler, 2013) and has shown drastic improvements in cooperation (Zimmermann et al., 2014) during lane changes. Its natural interaction will also be supportive for related problems, such as coordinating highway junctions, supporting freeway entry, collating vehicles from ending lanes, or merging trucks—both for cooperation within cars and between drivers. Consequently, Eriksson et al. (2019) showed that the corresponding user interface elements improve information analysis and decision making.

Knowing the drivers' *subjective perception of cooperation* (Zimmermann et al., 2015) is especially useful for presetting a driving-automation's maneuvers. Subjective perception will be of utmost importance for traffic coordination, because the user's ideal and the objectively

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[1] "If you want to evaluate a tool, say an axe, you might study the design of the bit, the weight distribution, the steel alloy used, the grade of hickory in the handle, etc., or you might just study the kind and speed of the cuts it makes in the hands of a good axeman" (Scriven, 1967, p. 53).

calculated, global optimum will differ. In case of doubt, suboptimal, but subjectively well-perceived traffic management, will trump optimal numeric performance as long as humans are involved in traffic. The good news is that humans esteem well-coordinated cooperation!

Since cooperation is subject to individual and social circumstances, this dissertation demonstrates game-theoretically powered, gameful interaction to *motivate cooperation* by using a strategic trade-off game and a reputation-based social-status game (Lütteken et al., 2016; Zimmermann et al., 2018). These concepts will strengthen both short-term maneuvering and long-term strategies between road users operating under different automation levels. The experiments show how to use social interaction to keep drivers committed to strategies and maneuvers. Social interaction can prime and shape drivers' behavior to accord with the coordinated traffic optimum—even if this would conflict with the individual's goal.

…to there!

Whenever intelligent traffic-coordination technologically (cf. Wang et al., 2016, 2015) becomes reality—regardless of whether manual or automated driving is being deployed—this dissertation provides suitable interaction and user interface concepts that support the drivers' anticipation of maneuvers and accordance with strategies. Shallow market penetration will not be a showstopper, and even small proportions of smart vehicles will yield performance improvements (Minderhoud, 1999; Moriarty & Langley, 1998). Meanwhile, the interaction concepts wouldn't even require automated, smart, or connected cars; sophisticated, distributed, V2V communication; or innovative, expensive user interface technologies. Reliable cellular communication, cloud computation powered by smart algorithms, and a standard smartphone (Hochwieser, 2015) would be a viable path to cooperation and would scale up in the near future.

Woods (2016, p. 10) brings Doyle's Catch into play: it's "relatively easy to demonstrate almost everything, provided that conditions are made sufficiently idealized," hence interactive systems should strive for "the real thing." Although the former's ease belies the prototyping complexity of cooperative systems, it should be added that over-simplified design, sold as "beta" (see chapter 1), will mislead into trust in automation (cf. Körber & Bengler, 2014). The real thing challenges the interaction concept at hand, which showcases a lane-change situation in driving simulations. Although it's taken a first step into the real world (Hochwieser, 2015), the interaction has to diversify across driving situations. Urban areas present more complex challenges for cooperative interaction: coordinating intersections, arbitrating between drivers stuck in rush-hour traffic, guiding drivers through phased traffic lights competitively, negotiating adaptive speed limits, or jointly finding parking spaces are just a few examples.

Urban areas will challenge cooperative systems twice. First, inhabitants of smart cities will interact in mixed traffic. Pedestrians could cooperate with cars, cyclists with electro-cyclists, and the latter with tramways for example. Playful interaction concepts could prevent danger (a driver gets informed about the approaching bike around the corner), use playful concepts to mitigate hindrance (a cyclist gives way to a faster e-bike, which carries another biker in its slipstream), or optimize performance (traffic lights that competitively optimize phases for approaching pedestrians, cyclists, and cars). Second, future cities will involve mobility as a service. Their inhabitants will change various transportation means based on volatile criteria. Getting to work for example could become a cooperative game, that provides a walk, bike, subway, taxi, or even plane just in time, well-motivated and coordinated through cooperation.

This, of course, is a distant vision. Until then, the ten design recommendations in this dissertation (see chapter 5) are applicable across domains. Some of them, formulated in design-pattern language (see Baumann et al., 2014b), have already demonstrated their proficiency at eliciting cooperation between humans, humans and machines, and human-machine systems—by water, land, and air.

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Supervised theses

The author of the present doctoral dissertation has supervised the students' theses listed in the sequel.

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Nomenclature

cACC Cooperative adaptive cruise control

cLCA Cooperative lane-change assistant

D3CoS The European research project D3CoS—designing dynamic distributed cooperative human-machine systems—has been funded by the ARTEMIS Joint Undertaking under the number 269336-2 (http://www.d3cos.eu/).

HCI Human-computer interaction

HFauto The European research project HFauto—human factors of automated driving—has been funded by a Marie Curie initial training network (http://hf-auto.eu/).

HTML5 Hyper Text Markup Language version 5 is standardized by the WHATWG (https://whatwg.org/) and W3C (https://www.w3.org/).

O The slow obstacle is the reason why the right-lane vehicle needs to change lane in the cooperative scenario.

OpenGL Open Graphics Library, an application programming interface for high performance graphics (https://www.opengl.org/)

PHP A general-purpose scripting language (https://www.php.net)

SILAB A driving simulation software platform (https://wivw.de/en/silab)

TTB Time To Breakup is defined as the time left for successfully coordinating a cooperative lane change

UML Unified modeling language (http://www.uml.org/)

V2I Vehicle-to-infrastructure communication

V2V Vehicle-to-vehicle communication

V_L The left-lane vehicle cooperates by opening a gap in the lane-change scenario.

V_R The right-lane vehicle is supported when changing lane in the cooperative scenario.


pressure
subjective
trade-off
gamification
decision
perception
between
automated
game
simulator
system
goal
interface
implementation
concept
study
request
multimodal
traffic
scenario
road
coordination
evaluation
across
future
work
strategy
automation
driver
time
model
cooperative
cooperate
state
following
research
safety
human
behavior
social-status
performance
perspective
information
question
paper-based
shared
different
left-lane
situation
speed
two
one
interaction
action
car
game-theory
phase
maneuver
element
experiment
analysis
approach
form
cooperator
motivation
vehicle
support
suggest
user interface
lane-change
first
control
turn
important
participant
factor
level
gap
social
need
driving
metric
within
improve
design
user
timing
acceptance
right-lane
communication
individual
human-machine
motivate
driving-simulator