Presented at the 2017 IEEE International Conference on Intelligent Transportation Systems (ITSC)
DOI: 10.1109/ITSC.2017.8317794

Rating Cooperative Driving: A Scheme for Behavior Assessment

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***Abstract*—The potential of cooperative automated driving to increase traffic flow efficiency and safety has awakened broad interest. Although research in this field is increasing and algorithms are varied, existing literature lacks an accepted taxonomy of cooperative automated driving and cooperative driving systems remain unrated. This paper introduces a novel structure to make cooperative automated driving rateable and further classifies existing works on cooperative behavior. The novel structure and the benefits of different cooperation modes are illustrated by several use cases.**

***Index Terms*—cooperative driving, cooperative automated driving, cooperative behavior planning**

I. Introduction

In the past 30 years driver assistance systems and automated driving have experienced tremendous progress [1]. The success of vehicle dynamics stabilizing systems in reducing the number of fatal accidents led to the development of accident warning and comfort systems, which have already solidified their place in the automotive market. The next step is the development of automated driving in which, depending on the level of automation, the vehicle either is partially or fully in charge of controlling the vehicle [2]. As the level of automation increases, robust and reliable operation of the automated vehicle plays an increasing role [3].

An automated vehicle can abort its operation because of a variety of reasons. Faults in the perception currently produce a substantial amount of total failures. Utilizing multiple and redundant sensors with different measurement principles have the potential to reduce them. Besides the utilization of the vehicles own sensors, a further option is to communicate with other vehicles and the infrastructure as well, and consequently share the percepted environmental information and vehicle intentions. If this *telematic* sensor information is utilized, the vehicle's own sensor measurements can be supported with information of high confidence. Furthermore, areas out of perception range or occluded by other objects could also be perceived in case they are within communication range. Such a communication would allow a higher level of *cooperation* among vehicles and enables a novel form of conflict resolution which eventually has the potential to increase safety and traffic flow efficiency [4].

The research leading to these results has received funding from the German collaborative research center "SPP 1835 – Cooperative Interacting Automobiles" (CoInCar) granted by the German Research Foundation (DFG).

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After the first successful demonstrations of cooperative automated driving in 1990s with the California PATH program, where a handful of vehicles formed a string stable platoon on a highway [5], there have been many publications in this field. Several projects around the world [6]–[8] have successfully demonstrated the theoretical findings and highlighted the potential of cooperative perception and behavior planning. Up to date surveys on cooperative driving are presented in [9], [10].

A fundamental requirement while evaluating cooperative automated driving systems is standardization and categorization. For cooperative vehicles equipped with different software and hardware to communicate and operate in harmony, standardized protocols are required. Although C2X communication sets have been standardized already [11], the different forms of cooperation achieved by automated vehicles are not categorized and furthermore, there is no common understanding of what cooperative driving is.

Therefore we introduce a systematic evaluation and rating of cooperative behavior revealing the different levels of cooperation. This categorization eases the understanding of which problems a cooperative driving technique is dealing with and can serve as a guideline for addressing the requirements on cooperative automated driving.

This paper is structured as follows: Section II provides an overview on existing definitions of cooperation and the aspects of cooperative automated driving. Following, in Section III, a novel structure to rate cooperative behavior into different levels is introduced. For a better understanding these levels are illustrated in Section IV. Then, Section V categorizes state-of-the-art systems on the basis of the proposed levels of cooperative behavior, before the paper ends with highlighting conclusions and future research directives in Section VI.

II. Definitions & aspects of cooperative driving

It is frequently pointed out, that literature currently lacks a common understanding of cooperative behavior [12]. Therefore, we first present a brief overview of existing definitions with regards to automated driving. We then identify similarities between them to find a set of important properties a common understanding should address. We restrict our overview to the most prominent definitions. Further definitions of cooperative driving and a survey of the terminology of cooperation is presented in [12] and [13].

A. Definitions of cooperative driving in literature

Communication is an important aspect of cooperation as can be seen from the literature emphasis on that topic, e.g.

in [14]–[16].

Aramrattana *et al.* [14] define cooperative intelligent transportation systems (C-ITS) as “technical systems that implement cooperative behavior based on communication”. They further claim that the act of sharing information alone is not enough for a system to be considered cooperative.

Another work by Sawade *et al.* [15] focuses on cooperation achieved by dedicated C2X communication. They present an overview of existing automated driver assistance systems and how these can be enhanced by cooperation as well as further conceivable cooperative automated driver assistance systems (CoDAS). Additionally, they introduce a method to classify CoDAS functions based on their communication requirements into “implicit”, “explicit” and “collaborative”.

Ulbrich *et al.* [13] consider C2X not as an enabler for communication but rather as an additional communication channel to the already existing channels like indicators, signal horns or brake lights. Based on this, they introduce a two-dimensional matrix to structure cooperative driving tasks. These tasks can be classified by the used communication channel and the abilities and skills needed to fulfill them.

A different approach to cooperation without the use of dedicated C2X communication is presented by Naumann *et al.* [17]. The authors define a 5-level structure to rank cooperative driving with respect to behavior planning. This approach mainly addresses how own behavior choices affect other traffic participants and how this feedback loop can be integrated into motion planning.

A concept based on a total utility to decide whether an agent is acting cooperatively is introduced in Düring *et al.* [12]. They point out that an important feature of cooperative behavior is that this behavior “willingly and knowingly increases the total utility of participating road users [. . .] compared to a reference utility”. If the behavior is unintentional or the agent is forced to a certain behavior by “legislation or by physical law” the agent is not said to act cooperatively. Furthermore an agent is not inherently cooperative, rather is cooperative an attribute of an agent’s behavior with respect to other agents.

A more general definition is presented by Zimmermann *et al.* [16]. Their main idea is that cooperative agents share common goals and compete for limited resources. The investigation is focused on Human-Machine cooperation and three “modes of cooperation”: the “perceptive”, “mutual control” and “function delegation mode” are identified.

B. Aspects of cooperation

As seen in Section II-A common literature on cooperative driving examines various aspects of and their influence on cooperation. Some define cooperative behavior in a broad general manner while others define it with focus on a specific detail of cooperation e.g. communication. However, there is no clear agreement on a definition of cooperative behavior in general and no clear understanding of how to measure or rate cooperation.

We derive the following important aspects from existing definitions which a common understanding of cooperative behavior should address:

- Behaving cooperatively is a way of working together, hence at least 2 agents are needed for cooperation.
- Behavior has to be executed willingly and knowingly with the intention to work towards a common goal.
- A model of a common goal and a mechanism to measure it is needed.
- A common understanding has to include road participants with different automation levels (heterogeneous traffic).
- Cooperation is possible using various communication channels, thus C2X communication is not a prerequisite for cooperative behavior. E.g. cooperative behavior can already be observed in nowadays traffic where C2X is not widely available [13].

In our view cooperation can be best described as a mechanism of working together on a common goal with the use of limited recourses, as mentioned in [16]. This way traffic can be seen as an optimization problem, with the common goal to optimally use the limited and shared infrastructure under the prerequisite of safety, such that ideally each agent can reach its destination under its individual preferences of comfort and efficiency.

We therefore call cooperative behavior an action that is willingly and knowingly executed with the intention to work towards this common goal, bringing the assemble closer to an overall optimum.

III. Levels of Cooperative Driving

In order to categorize cooperative behavior and to decide whether an action is cooperative or not, a way to measure cooperation has to be defined first. This can be achieved with a quantifiable utility for each agent based on the factors comfort, efficiency and safety, and a total utility as a combination of all agents’ utilities similar to Düring *et al.* [12]. The better traffic participants cooperate, the potentially higher the total utility.

Nowadays traffic rules’ purpose is to work towards this goal mainly by optimizing the throughput and providing safety. Cooperation is a mechanism to further optimize traffic especially in situations where current traffic rules favor none of the traffic participants, or in scenarios in which better solutions to the ones provided by traffic rules can be found.

A. Explicit and implicit communication

We differentiate between 2 types of communication: *implicit* and *explicit*. Implicit communication is communication where the primary purpose of an action is not to communicate but rather to fulfill a different task. E.g. a traffic participant can communicate implicitly through its movement without intending to do so. An observer, however, could estimate data like position, velocity and maneuver intentions from this movement and predict future motion.

Explicit communication is an action where the primary purpose of this action is to communicate. E.g. a traffic participant using an indicator signal or sharing its planned trajectory via C2C to communicate its maneuver intentions is communicating explicitly. A characteristic is that additional effort has to be made besides the main driving task.

Generally implicit communication comes with higher uncertainty due to the fact that information is obtained by measurement and estimation. E.g. when a car is driving close to the border of its lane one could derive a lane-change intention from this behavior. But the driver could also drive close to the border without any intention to change the lane. Explicit communication therefore has the potential to drastically increase the fidelity of measurements and can improve the sensing horizon.

B. Ranking cooperative behavior

Based on the description of cooperation introduced earlier, we distinguish between two major categories of cooperation: *information based* and *maneuver based*. We furthermore suggest a hierarchical structure to rank cooperative behavior according to the potential each level has to reach the system overall optimum. A detailed overview of the key features is presented in Table I.

Information based (IB) cooperation describes an agent's act of explicit information sharing such as sensor data, system state and intentions, without explicitly considering a total utility. Even though these agents are only optimizing their own utility, they willingly and knowingly share data to improve other agents' utility mainly by increasing their sensor range and fidelity thereby increasing the total utility.

Maneuver based (MB) cooperation describes an agent's adaption of its driving behavior by willingly incorporating other agents' utility into its own behavior planning in order to increase the total utility compared to just optimizing its own utility.

A traffic participant's cooperative behavior can therefore be information based, maneuver based or both. As an example, a vehicle sharing its ESP status is IB cooperative. If it simultaneously adapts its velocity to allow another vehicle to merge into traffic under comparably low own disadvantage, it is also MB cooperative.

C. Levels of information based cooperation

IB1 cooperative perception: An agent explicitly sharing sensor data like detected obstacles or its state information like current velocity is cooperating on a perceptive level.

This enables agents receiving this data to drastically extend their sensing horizon and reduce perceptive uncertainties, thus significantly improving the total utility by increasing overall safety and optimizing their utility.

IB2 cooperative prediction: If additionally to IB1, data about future actions like intentions and planned maneuvers is explicitly communicated the benefit to the total utility is even higher. This enables receiving agents to reduce their prediction uncertainties, again increasing safety, their individual comfort and efficiency.

Increase in Total utility ↓

0 Non-Cooperative Behavior
- Implicit communication
- Optimizes own utility

MB1 Cooperative Planning
- Implicit communication
- Optimizes estimated biased total utility

IB1 Cooperative Perception
- Explicit communication of
  - Sensor data & state information
- Optimizes own utility
- → Tightly coupled perception

IB2 Cooperative Prediction
- Explicit communication of
  - Sensor data & state information
  - Intentions & maneuvers
- Optimizes own utility
- → Tightly coupled perception & prediction

MB2 Negotiated Cooperation
- Explicit communication of
  - Sensor data & state information
  - Intentions & maneuvers
  - Maneuver options & associated utilities
- Optimizes biased total utility
- → Tightly coupled perception, prediction & planning

MB3 Collaboration
- Explicit communication of
  - Sensor data & state information
  - Intentions & maneuvers
  - Maneuver options & associated utilities
- Optimizes fair total utility
- → Tightly coupled system

Table I: Hierarchical order of the levels of cooperative behavior and their key features.

D. Levels of maneuver based cooperation

1) MB1 cooperative planning: An agent planning cooperatively uses a total utility estimate for its behavior and trajectory planning. As soon as it adapts its behavior to a maneuver with a higher estimated total utility, compared to a reference behavior which maximizes its own utility only, it is rated MB1.

At this stage the agent estimates the total utility locally and can give weight to other agents' utilities at will, given that each agents interests are ensured at least to a minimum extend. This circumstance leads to a biased total utility estimate. Consequently a rather egoistic agent for example would only change its driving behavior in order to increase another's utility and thus plan cooperatively if its own disadvantage is comparably small to the others advantage. A potential problem of utility estimation is that each agent ends up with its own biased estimate which could lead to contradictory maneuvers and hinder cooperation.

Cooperative planning can be achieved through the use of implicit communication only, but can be further improved with IB1 or IB2 cooperation.

2) MB2 negotiated cooperation: The next level of cooperative behavior requires the agent not only to consider the utility of others, but also to negotiate with them which coordinated maneuver to chose. In order to achieve this ability it is necessary for the agents to explicitly exchange maneuver options and associated utilities with each other.

As the total utility is not estimated locally anymore, but its components communicated explicitly, this level drastically reduces utility estimation errors. Additionally the agents possibly generate new, coordinated maneuvers with higher total utility than it would be possible without an agreement.

As in MB1 an agent can still give weight to others utilities at will, but might be willing to improve others utility weight in its biased total utility calculation, for example in exchange for a substitute value. This could be money, travel time credit, reputation of trust, memories of cost or other yet to develop substitutes [18]. A substitute value is especially handy in deadlock situations like an intersection with cars at each road section where all participants have similar utilities and traffic rules favor none of them.

Explicit maneuver and utility exchange implies that all participating agents satisfy MB1 and the information based cooperation level IB2. It also requires a standardized representation of behavior options and their utility function elements and a standardized channel and protocol for negotiation.

3) MB3 collaboration: The highest level of cooperation can be achieved if an MB2 cooperative group considers each agents utility equally in the total utility calculation leading to an unbiased total utility.

For successful collaboration every participating agent has to satisfy MB3 and stick to the best solution without objections. This solution can be obtained in a distributed manner or with the aid of a centralized traffic management. As a result a collaborative ensemble does not need traffic rules or fixed width lanes, enabling even more optimal solutions.

Safety and trust mechanisms are not part of this work but as already motioned in [13] an individual agent could gain personal benefit by communicating inappropriately high costs. Therefore some mechanism that guarantees trust is needed in MB2 and MB3.

IV. Use Cases

The following examples illustrate how cooperative behavior can improve the total utility.

A. Occluded Pedestrian

The scenario shown in Figure 1 illustrates the effect *IB1 cooperative perception* can have on the total utility.

A pedestrian is approaching the street next to a parked truck. Vehicle *A* is unable to detect the pedestrian due to occlusion. Relying solely on its own perception this leads to a potentially dangerous situation especially with an unobservant pedestrian. By explicitly communicating its sensor data vehicle *B* can inform *A* about the detected pedestrian. This shared information enables *A* to overcome the occlusion, which drastically increases safety for all traffic participants.

B. Intersection

In Figure 2 vehicle *A* and *B* are approaching an intersection. *A* has the intention to do a left turn. *B* is approaching the intersection from the right with the intention to take a right turn and has the right-of-way.

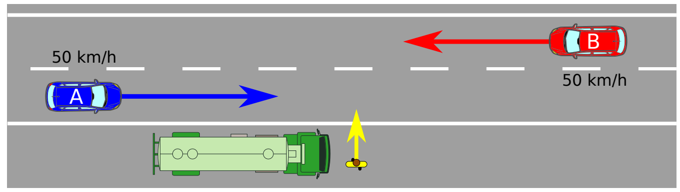

Figure 1: IB1 cooperation allows to perceive occluded areas, increasing safety for all traffic participants.

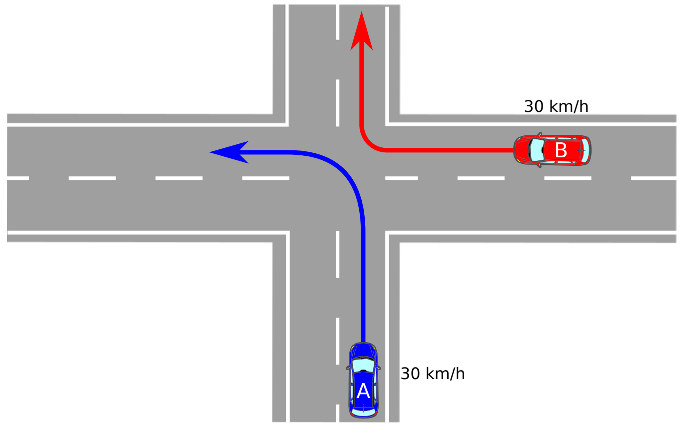

Figure 2: Sharing maneuver intentions allows to pass the intersection more efficiently, avoiding unnecessary braking.

The effect of *IB2 cooperative prediction* can be best illustrated considering the utility of *A*.

If the vehicles are not communicating explicitly, *A* would reduce its speed while driving towards the intersection possibly coming to a full stop. Due to *B* having the right-of-way *A* has to wait until *B* has cleared the intersection.

By explicitly communicating its maneuver intention, e.g. transmitting a trajectory via C2C, *B* is acting on the *IB2 cooperative prediction* level. This provides *A* with the opportunity to potentially find a better maneuver increasing its utility. E.g. since *B* will take a right turn *A* can pass the intersection at the same time to do a left turn, without unnecessary deceleration.

C. Highway on-ramp

The next scenario seen in Figure 3 shows vehicle *A* driving on an on-ramp with the intention of merging onto the highway. On the right lane of the double tracked highway vehicle *B* is approaching the merge location with significantly higher speed than *A*. The impact of MB cooperative behavior and the possible increase of the total utility compared to non-cooperative behavior is best illustrated considering the behavior of *B*.

If *B*'s behavior is non-cooperative, e.g. the lateral and longitudinal control is done using ACC and a lane-keeping assistant, *B* would only alter its maneuver if there is an upcoming safety critical situation. That means as long as *A* is not changing lanes unexpectedly and endangering both traffic participants *B* would keep driving on its lane with its desired velocity. This is *B*'s reference behavior which is coherent with traffic legislation and optimizes *B*'s utility only.

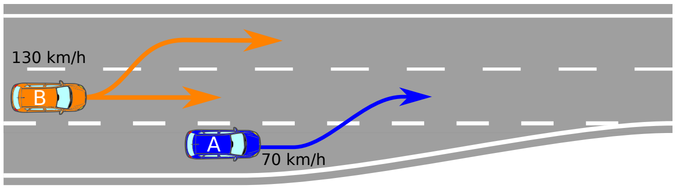

Figure 3: MB1 cooperation allows vehicle *B* to clear the right lane enabling *A* to smoothly merge onto the highway.

The first step to maneuver based cooperation is to take into account how the utility of others is affected by own maneuver choices. Even without explicit communication *B* can estimate *A*'s utility based on its own perception and predict a merge intention. As soon as *B* decides to change its behavior with the intention to increase the total utility compared to the reference behavior it is acting on a MB cooperative level.

For example *B* predicts the intention of *A* to merge onto the highway and estimates high costs for *A* due to strong acceleration or deceleration if *B* sticks to the reference behavior. After estimating the total utility for different maneuver options, e.g. strong acceleration, strong deceleration, lane change, *B* decides to change onto the empty left lane enabling *A* to smoothly merge onto the highway.

By doing this *B* willingly choses a maneuver to increase the utility of *A* at the price of decreasing its own with the expectation that the benefit of *A* will outweigh the own disadvantage.

D. Cooperative Overtaking

Figure 4 shows vehicle *A* driving on a country road catching up to a slow traveling truck. On an non-cooperative level, overtaking is not possible due to traffic on the opposite lane such that *A* has to brake.

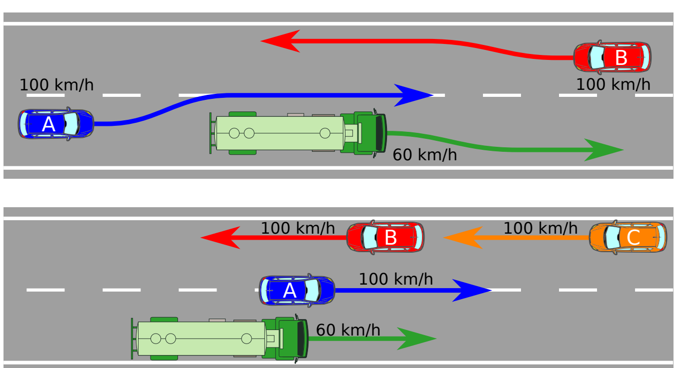

Figure 4: MB2 cooperation enables traffic participants to agree on a coordinated maneuver, creating an ad-hoc third lane and thereby optimizing the total utility.

If all traffic participants are capable of at least *MB2 negotiated cooperation*, they have the opportunity to negotiate a common coordinated maneuver which increases the total utility. This common coordinated maneuver does not necessarily need to obey existing traffic legislation. E.g. if the road section is wide enough the cooperative maneuver could involve an ad-hoc creation of a third lane as seen in Figure 4.

Although the individual utilities are communicated the decisions are made locally with a biased total utility in favor of the vehicle with right-of-way. This means in the Figure 4 vehicle *B* or *C* would still be able to bias the total utility to the extend where no alternative maneuver is chosen anymore and no cooperation will take place.

If on the other hand all traffic participants fulfill MB3 collaboration there is no local decision making, but maneuver planning is solved as an holistic problem for the whole system weighting every agents utility equally.

V. Rating Existing Cooperative Automated Vehicles

The rating scheme proposed in the previous section applies well to existing works. In this section we will categorize some existing cooperative automated vehicles.

Most of the existing works either utilize level IB1 or IB2. Cooperative Adaptive Cruise Control (C-ACC) as an extension to ACC can be categorized into level IB1 as long as only current state information is shared. The most prominent examples of this level are the vehicles of the first Grand Cooperative Driving Challenge (GCDC) [19]–[22]. Other works have further utilized a communication framework for sharing planned maneuvers such as the vehicles in California PATH program [23], the Demo 2000 [6] and the vehicles in 2016 GCDC [8]. These vehicles can be categorized into IB2 cooperative prediction.

Although there are many works investigating level MB2 negotiated cooperation within a simulation environment, such as [24], [25], to the best of the authors' knowledge, there has not been any demonstration with real vehicles.

Although the proposed rating scheme allows a systematic evaluation of cooperative behavior, it does not cover other aspects such as the effects of wireless communication [26] or the degradation of C-ACC [27]. These must also be considered while assessing the quality of cooperative behavior techniques.

VI. Conclusions and Future Work

In this paper we presented an overview of current definitions of cooperative behavior and named the lack of a common understanding. After summarizing the central aspects of cooperation, we introduced a hierarchical model to characterize cooperative behavior based on communication and a total utility. The total utility is a measure of how well the agents cooperate together. The introduced model should serve as a structure for a common understanding and provide a guideline on how cooperative behavior can be improved. The different levels of cooperation have been illustrated with several example scenarios. We concluded our paper with a short review of existing cooperative automated vehicle prototypes, providing an insight on which levels already have been addressed by research and which levels need further studies to improve cooperative behavior. The specific definition of the quantifiable utility function is current research and will be addressed in future publications.

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