A Cooperative Driver Assistance System: Decentralization Process and Test Framework

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Abstract— **Cooperative Driving has attracted significant attention in recent years. With the help of vehicle-to-vehicle (V2V) communication, perception systems may increase their quality of signals, their availability, and their perception range as well as decrease their latency and probability of failure. Moreover, V2V communication enables advancements from individual to cooperative decision making. With the help of a decentralized decision making among road users, the compatibility of varying planning algorithms distributed on several vehicles can be guaranteed. Additionally, the presented approach offers the opportunity to preserve the autonomy of decision making for each vehicle with an integrated validation. The integrated validation declines contradicting maneuvers by applying internal functional safety rules. The increasing progress in the research of cooperative technologies imposes new requirements for testing and validation. Therefore, a modular test framework regarding both the simultaneous integration of several autonomous vehicles and characteristics of a V2V based peer-to-peer communication is described. A combination of ADTF (the application prototyping framework within the Volkswagen group), VTD (a simulation tool-chain of VIRES) and OMNet++ (an open-source component-based network simulator) allows a host of experiments to test and validate cooperative driver assistance systems. In order to prove the decentralization process and the test framework, the paper shows simulation results for a cooperative safety system and a cooperative comfort system.**

I. Introduction

The attention on Cooperative Driving has significantly increased in recent years. Several publications show the potential benefit within perception and decision making [9]. In order to increase the quality of signals, the availability and the perception range as well as decrease the latency and the probability of total failure, advanced perception systems combine camera, radar and lidar systems with vehicle-to-vehicle (V2V) communication [5, 14, 18]. Moreover, V2V communication enables advancements from individual to cooperative decision making. Advanced driver assistant systems, which determine their behavior in due consideration of the definition of "cooperative behavior" [3], are capable of increasing the total utility of a group of cooperative vehicles [4, 26]. Even though several publications present planning algorithms for driving/conducting cooperative maneuvers [4, 7, 28], the decision making for cooperative driving remains a challenging research topic. Especially, the decentralization of decision making and the preservation of autonomy are key aspects to be elaborated.

A comparison of approaches concerning cooperative behavior for automotive use shows implementation of varying degree of maturity. They reach from a concept to a software implementation through to a hardware demonstrator. Each analyzed paper proves the usability and performance of their approach with the help of some kind of measurement data. In order to realize this usability analysis, a host of test methods from a SiL (Software-in-the-Loop) to a HiL (Hardware-in-the-Loop) through real world experiments are proposed. Some papers use a SiL within their own implementation framework in order to test a cooperative intersection crossing [1], or to address merging, overtaking and gap adjustment of platoons [15, 19, 27]. The authors of [8] combine miniaturized autonomous vehicle with a central sensor system as a testbed. Since platooning is a considerable research topic for several years, there are projects conducting field tests with real vehicle [14]. However, a simulation framework capable to accompany the development of cooperative driver assistance systems (CDAS) from the early concept to field test with a variety of test methods (further details to test methods [10]) is still missing. Within the field of automotive testing the well-known simulation frameworks CarMaker [24] and Virtual Test Drive [11] support the required test methods but do not provide any modules for connected vehicle.

II. Problem Statement

Several technical issues have to be solved on the way to the first CDAS on public streets. The authors of [6] expose among others driver acceptance, handling of misuse of the communication channel, the consideration of unequipped vehicle, and uncertain knowledge as key challenges for cooperative driving.

This paper focuses on two aspects of CDAS. The first aspect is the contradiction of autonomy and mutual influence. On the one hand, in order to guarantee product liability, each vehicle (automatic system) strives to make decisions autonomously (self-sufficient, independent, synonyms by [17]). On the other hand the benefit of CDAS depends on the mutual influence of the vehicle. The second aspect is the need of a test framework, in order to master the complexity of distributed driver assistance systems (DAS) already during the development process.

The paper is structured as follows. In the proceeding section, a method of decentralized decision making for CDAS is presented. The following section describes

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a flexible test framework dealing with the challenges of inter-vehicle connectivity. Afterwards, simulation results demonstrate the usability of both the decision making process and the test framework. The last section completes the paper with the conclusion and outlook.

III. Decentralized Cooperative Driver Assistance System

The authors of [6] present an architecture that is capable of realizing CDAS. The mentioned approach bases on an advancement of deliberative control architecture. The process starts with the recognition and transmitting of the demand of cooperation. Afterwards, in order to generate a preferably complete common environmental model, the vehicles share relevant information with each other. Using this environmental model, cooperative planning algorithms can calculate possible solutions (offers of cooperation) to resolve the conflict situation and exchange them within the group of concerned vehicles. Possible conflict situation cover use cases for efficiency, comfort as well as safety applications. The decision making process for a commonly accepted maneuver consists of an evaluation, a selection, and a validation. Furthermore, a CDAS requires a module to monitor the correct maneuver execution. This papers assumes, that there are well-known algorithms to calculate coordinated cooperative driving maneuvers to solve conflict situations. For further details please review [4, 7]. The following sections describe the decentralized decision making process separated in the tasks Offer of Cooperation, Evaluation of Cooperation, Selection of Cooperation, and Validation of Cooperation. This process will ensure a minimum of co-management and the handling of uncertain and non-identical knowledge.

A. Offer of Cooperation

In order to solve conflict situations, planning algorithms determine feasible maneuver plans P. The involved vehicles exchange these plans P as Offers for Cooperation via V2V-communication. A clear plan representation (Offer of Cooperation Message, *OCM* [6]) has to guarantee an unmistakable interpretation of the intended driving maneuver. A plan P consists of one trajectory for each cooperative vehicle (Figure 1). The combination of a sequence of fifth order splines for path representation and an acceleration profile for longitudinal dynamics forms a plan (Figure 2). The figure illustrates a plan consisting of two splines and a sequence of three constant longitudinal accelerations. The five coefficients of Equation 1 describe the spline.

$$Y = C_5 \cdot x^5 + C_4 \cdot x^4 + C_3 \cdot x^3 + C_2 \cdot x^2 + C1 \cdot x + C_0 \quad (1)$$

The initial conditions of the first spline are defined by the vehicle state z_0 (x_0, y_0, t_0, ϕ_0). The initial conditions for the following splines accrue from the required tangentially constant spline characteristic. It is possible to use a spline to represent the longitudinal acceleration, too. For the shown example a sequence of first order splines satisfies the requirements. In an initial approximation, this paper does not require a tangentially constant characteristic of the longitudinal acceleration. Note that the acceleration profile is represented as a function of time $a(t)$ and the path is represented as a function of space $y(x)$. In order to guarantee a correct interpretation of the plans, a common accepted coordinate system must exist. There are several possible coordinate systems to represent the path. The initial position refers to a global coordinate system like GPS, to one vehicle in the group as a fully relative coordinate system, or as a combination of both relative to the lane markings using the *Frenet*-coordinates d and s. The variable s, longitudinal position along the path, is defined as zero for the position of one vehicle at t_0. The variable d is defined as the lateral offset to the right lane marking. Current environmental sensors are capable of accurately measuring the relative distance between the vehicles as well as the offset to lane markings, hence to the best of the authors' knowledge *Frenet*-coordinates are the preferred coordinate system. A global positioning system fulfilling the accuracy requirements of lateral and longitudinal control is very expensive [12]. If a fully relative coordinate system is used, slight deviations of heading will cause high errors of lateral offset due to the high sensitivity of orientation errors. As the preferred coordinate system (*Frenet*) requires a vehicle as initial point, it is assumed that the vehicle broadcasts the demand of cooperation.

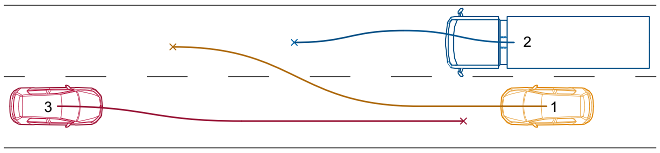

Figure 1. Plan for three participating vehicles for a cooperative driving maneuver.

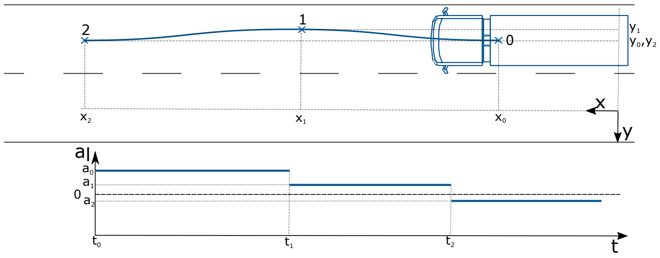

Figure 2. Description of a trajectory for a cooperative driving maneuver consisting of a path and an acceleration profile.

In order to realize an increased total utility function as mentioned in the definition of cooperative behavior, the Evaluation of Cooperation uses a mutual assessment of costs for the Offers of Cooperation. Each vehicle $v \in [1, \text{number of vehicles f}]$ describes the costs of a plan p_i ($i \in [1, \text{number of offers n}]$) as a scalar $k_{i,v}$. The idea is, that a combination of subjective individual cost assessments forms an objective total utility function. Several paper address the problem of modeling costs for driving maneuver [13, 23]. This paper refers to [2], which uses a cost function to assess cooperative driving maneuvers modeling four separate domains (safety, comfort, efficiency and driving enjoyment). The used cost function is based on an implementation of a fuzzy logic. Due to the mutual assessment (combination of individual assessment) each vehicle can use different cost functions. The differences of the cost functions can be a consequence of variation of the weights of the domains (safety, comfort, efficiency and driving enjoyment) or of a completely different implementation. In order to ensure an interoperability of the subjective individual assessments, a common value range D for costs must be defined. The equation below shows the exemplary definition of value range.

$$D = \begin{cases} [0,1] & \text{for valid plans,} \\ \infty & \text{for invalid plans.} \end{cases} \tag{2}$$

The subsection Validation of Cooperation focuses on the criteria to classify between valid and invalid plans. An additional advantage of the distributed assessment is that the individual assessment of plans does not require an identical environmental model. Differences in the data exist even with exchange of information via V2V due to synchronization errors and varying assumptions within the mathematical models. At this point the idea could arise that each vehicle principally prefers the self-calculated plan. Due to the fact that OEMs mainly focus on the customer wish, it is not reasonable to principally prefer a self-calculated plan. The individual cost functions model the customer wish and it is irrelevant to the customer, which vehicle generated the best plan.

B. Selection of Cooperation

The selection of the best plan $P_{opt} \in \{P_1 \ldots P_n\}$ can operate with a variety of criteria. Here, the selection criterion is either the minimum of a weighted sum of individual costs (Equation 4) or the minimum of the sum of the square of weighted individual costs (Equation 5).

$$Opt = arg\, min(K_i) \tag{3}$$

$$(a)\; K_i = \sum_{v=1}^{f} w_v \cdot k_{i,v} \tag{4}$$

$$(b)\; K_i = \sum_{v=1}^{f} (w_v \cdot k_{i,v})^2 \tag{5}$$

In comparison to (a) the selection criterion with the square of individual costs (b) will prefer plans with a lower variation of individual costs. The weight factors w_v depict varying importance of the vehicle. The varying importance can be caused by inherent priority (emergency vehicle, public transportation, etc.) or by acquired priority. The acquired priority implements the idea of a cooperative reward system, which realizes a long term fair deviation of the 'donor' and 'taker' role between vehicles. This paper refers to [20] for further details of long term fairness for CDAS.

C. Validation of Cooperation

Due to several reasons, a Validation of Cooperation is convenient. Firstly, the generated plans can be physically impossible, because of wrong assumption of the capabilities of the involved vehicles (due to violation of kinematic and dynamic constraints). Secondly, the plans may not fulfill the internal requirements regarding distances, relative velocities, or used lanes. The verification of these two criteria can already be accomplished within the Evaluation of Cooperation and leads to a refused plan (cost value of ∞). However, a re-verification before the final execution of the plan is still meaningful. On one side, the process for evaluation and selection including communication will take some time. The duration of the process is still unknown, but to the best of the authors' knowledge it might last some $10\,ms$. Within this period, circumstances may change the acceptance of the plan (e.g. new obstacles or changing of the road surface). Furthermore, due to lost messages within the Vehicular Ad Hoc Network (VANET), a verification that each vehicle selected the identical plan, is required. This verification can be an exchange and comparison of the unique plan id, already generated in the planning methods and used as a plan identifier during evaluation, selection and validation.

IV. SIMULATION FRAMEWORK

Since the development of CDAS requires at least two interacting vehicles, the implementation and the validation of the system necessitate a flexible test framework for connected vehicles. Figure 3 gives an overview of the proposed architecture used within this paper. The detailed description of interfaces and functionality follows hereinafter.

A. Application

A simplified illustration of the CDAS is composed of a planner implemented in ADTF (Automotive Data and Time triggered Framework) and a controller for each involved vehicle [16]. The planner generates offers based on the environmental model and the current vehicle state. The following decision making process consists, as mentioned, of an offer, an evaluation, a selection and a validation. Each step requires communication to exchange the results. The selected trajectory serves as a set value for the controller, which calculates the control value in order to influence the vehicle motion. Thereof, three relevant interfaces of the application to connected modules result. The first interface represents the environmental model and the current vehicle state provided by the simulation gateway. The second interface to the network enables the communication between vehicles. The last interface to the simulation gateway realizes the controllability of the vehicle.

B. Simulation Gateway

For each vehicle (here exemplary shown for three), the simulation gateway fulfills among others two tasks; the modeling of the perception (environment and vehicle state), and the reaction to controller outputs. The individual environmental models result from the projection of the virtual environment (ground truth) on the current vehicle state. This projection considers boundary conditions of the perception system like field of view, accuracy, and latency. Here, the environmental model consists of an object list and a graph representation of roads. The model, which calculates the current vehicle state, is based on a set of mathematical equations representing the vehicle kinematics. The current vehicle state influences both the planner and the controller. The combination of both uses the current vehicle state to calculate new controller outputs,

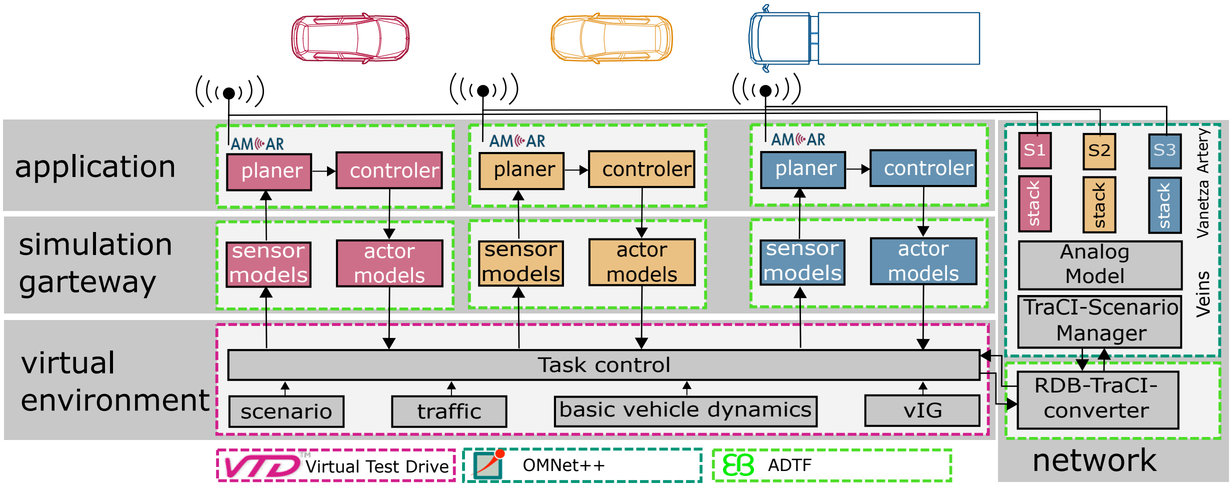

Figure 3. Overview of the simulation framework

which influence the current vehicle state and thus creates a feedback loop. The interface for the vehicle state includes, but is not limited to, the velocity, the longitudinal and lateral acceleration, and the steering wheel angle. The majority of the vehicle state signals are available on a vehicle's powertrain CAN interface.

C. Virtual Environment

The software Virtual Test Drive (VTD) developed by VIRES provides the virtual environment [11]. The central component is the task control coordinating additional modules with the help of the module manager. Additional modules are the scenario with roads and vehicle information, the traffic, the basic vehicle dynamics for internally controlled vehicles and the Image Generator (IG). The virtual environment transmits its information via Ethernet on the Real Time Data Bus (RDB) interface. Furthermore, the Simulation Control Protocol (SCP) interface provides a mechanism for operating the simulation.

D. Network

The network simulation can emulate the communication of the application via for example, ETSI ITS G5. The following description of the communication starts at the application. AMCAR (Arbitrary Message Communication Architecture) gathers messages to be transmitted and provides received information. AMCAR enables, among others, the decoding and encoding of ASN.1[1] specified messages, the connection with the network simulator OMNet++, and transformation of coordinate systems. The instances of the ARTERY [22] components (here three, one for each communicating vehicle) accept the sending requests and transmit them to the stack. Additionally, ARTERY forwards the messages to the application. The following part of the network simulation is the ETSI ITS G5 stack modeled by VANETZA [21]. In order to allow the simulation of transmitting delays, channel congestion, and signal damping, the VANETZA model reaches the physical layer. The analog model attached to VANETZA simulates the analog signal characteristics. The analog model acts as the first component and is able to decide whether a vehicle can transmit/receive information or not. In order to simulate the signal damping, the analog model uses information about line of sight and distances between the communicating vehicles. The RDB interface and the map of VTD (*.xodr format) contain the required information. An additional ADTF component translates this information in TRACI (Traffic Command Interface), an interface originally developed to connect SUMO and OMNet++. For detailed information concerning the analog model please review [25].

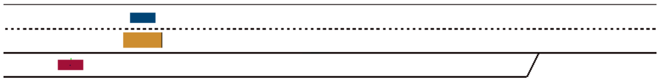

Figure 4. Merging scenario on a highway to demonstrate the usability of the decentralized decision making process, visualization with the 3D-Scene display of ADTF

V. SIMULATION RESULTS

A. Decentralized Decision Making

An example of a merging scenario on a highway is chosen to demonstrate the usability of the decentralized decision making (Figure 4). The red vehicle wants to merge onto the highway, while the two lanes are blocked by a truck (yellow) and another vehicle (blue). The lane width amounts to three meter. At the beginning of the maneuver each vehicle drives in the middle of its lane. The x value (x axis parallel to the lane, positive to the right) represents the distances between the vehicles' geometric center positions. The red vehicle has an x-position of 0 m and a velocity of $27,8$ m/s. The yellow truck has an x-position of 12 m and a velocity of $22,2$ m/s. The blue vehicle has a x-position of 12 m and a velocity of $27,8$ m/s. The dimensions of the vehicles are $1,77$ x $4,23$ m (passenger cars) and $2,56$ x $6,44$ m (truck).

The cooperative maneuver planning algorithms require information concerning the vehicle capabilities. Lateral

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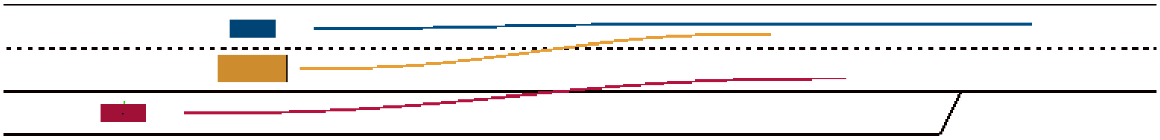
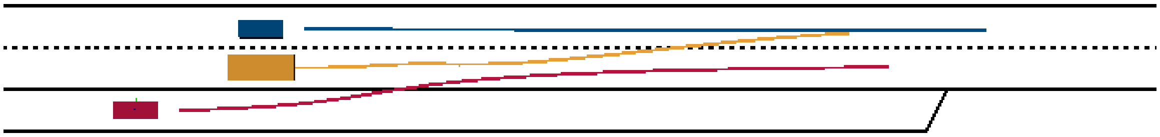
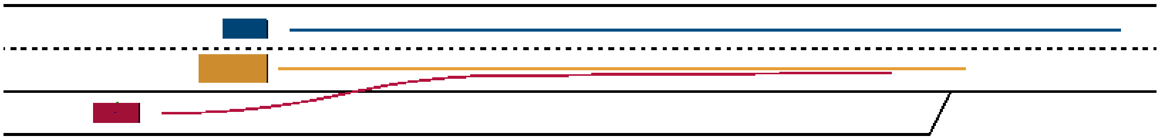
[1] Abstract Syntax Notation One



(a) Reachable Sets



(b) Elastic Bands



(c) Tree Planner

Figure 5. Results of the planning methods for the merging scenario

Table I. Preferences of the cooperative vehicle to parametrize the cost functions

	red vehicle	yellow truck	blue vehicle
safety	1	1	1
comfort	0.2	0.5	1
efficiency	0.1	1	0.4
driving enjoyment	1	0	0.1

Table II. Individual costs and combined costs for a cooperative merging scenario

	plan (a)	plan (b)	plan (c)
red vehicle	0.59	0.85	0.80
yellow truck	0.20	0.41	0.13
blue vehicle	0.44	0.17	0.17
sum $k_{i,v}$	1.23	1.44	**1.11**
sum $k_{i,f}^2$	**0.44**	0.93	0.69

and longitudinal acceleration (a_y and a_x) model the capabilities due to kinematics. For the red and blue vehicle $-7,00\ m/s^2 < a_x < 2,5\ m/s^2$ and $-5,00\ m/s^2 < a_y < 5,00\ m/s^2$ and for the yellow truck $-7,00\ m/s^2 < a_x < 1,5\ m/s^2$ and $-5,00\ m/s^2 < a_y < 5,00\ m/s^2$ are modeled.

Three different planning algorithms generate offers for the merging scenario. The three planning algorithms are based on reachable sets [2, 4], on a tree planner [7], and on elastic bands [7]. The planning algorithms are implemented in C++ within the ADTF framework. Figure 5 shows the result (offers) of the planning methods.

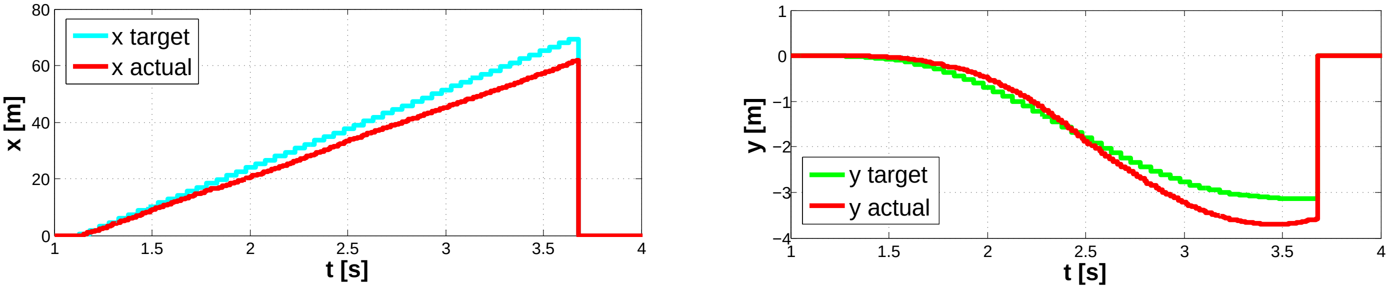
It is shown that the planning methods (a) and (b) recommend a lane change for the truck, while method (c) makes the truck stay on its lane. Planner (b) starts the lane change later than planner (a). Planner (c) solves the conflict situation by accelerating the truck and merging maneuver of the red vehicle behind the truck. The diversity of the offers results from different discretizations and different evaluation criteria. In order to demonstrate the decentralized decision making process, a cost function based on a fuzzy logic is applied, which enables a continuous prioritization between comfort, driving enjoyment, efficiency, and safety. Table I illustrates the different preferences of each vehicle. The truck focuses on efficiency, the red vehicle prefers driving enjoyment, and the blue vehicle prioritizes comfort.

Each vehicle comes to a different evaluation or rating of the offers, because of the varying preferences. The varying preferences can be caused by different brands, different vehicle models (sedan, van or SUV), or by an online driver monitoring system. Table II shows the results of the evaluation of each plan by each vehicle and the result of the two proposed selection criteria. The selected solution (bold) represents the compromise of the solution options. The plan (c) is selected by the sum criterion and plan (a) is selected by the squared sum criterion.

In this example the authors assume, that each vehicle has identical weight factors (evaluation as peers). The result will vary, if changed weight factors are used.

B. Closed Loop Simulation

The closed loop or hardware in the loop simulation enables a study to evaluate the control error considering communication and calculation latencies of planner, controller, and vehicle dynamics. An application for collision avoidance exemplarily demonstrates the closed loop performance. As an initial scenario a driver starts an overtaking maneuver on a rural road. The driver misjudges the situation and the danger of a collision with the oncoming traffic arises. An active safety system detects the danger and starts/triggers the cooperative maneuver planning. The detection criterion could also be the time to collision (TTC). The TTC is calculated as the quotient of distance and relative velocity. Here, the cooperative maneuver planning starts at a $TTC < 1,2\ s$. Thereof, the situation at the triggering time accrues (figure 6). The definition of the x-value is identical to the example above. The red vehicle starts at $x = 0\ m$ with a velocity of $27,8\ m/s$. The truck has an x-value of $5,2\ m$ with a velocity of $22,2\ m/s$. The



(a) longitudinal controller

(b) lateral controller

Figure 7. Results of the closed loop simulation

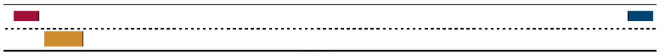


Figure 6. Scenario for collision avoidance on oncoming traffic, visualization with the 3D-Scene display of ADTF

blue vehicle is located at $x = 66,8\ m$ with a velocity of $27,8\ m/s$. The vehicle drives in the opposite direction of the other vehicles. The dimensions of the vehicles are equal to the first example. The calculated cooperative maneuver plan targets the completion of the overtaking maneuver of the red vehicle and a deceleration of the truck and the blue vehicle. Below an analysis of the control error of the red vehicle is given.

Two separate PID-controllers (lateral and longitudinal) in combination with a feed forward control are implemented. A vehicle dynamic based on a multi-mass model simulates among others pitching and rolling. Figure 7 shows a flagging characteristic. The longitudinal controller has a linear increasing controller error. This is caused by a constant velocity error. A possible reason is that the longitudinal controller does not model the decelerating influence of a steering maneuver. In this case the vehicle decelerates stronger than planned. The lateral controller shows an overshooting. The vehicle stays with 50 cm maximum controller error in a safe condition (stay on road, no collisions with obstacles). This error is caused by latencies and systematic errors in the feed forward controller. However, systematic errors, difference between vehicle dynamics model and inverted model in the feed forward controller, are made on purpose. A perfect vehicle dynamics model in the feed forward controller is impossible in reality, because of for example changing loads, changing wheel characteristics, and changing surface etc. Further controller adaption will be done with the help of real field test.

VI. Conclusion and outlook

With the help of communication and special planning methods, it is possible to cooperatively solve conflict situations. The proposed decentralized decision making process selects a compromise of the offers considering different planning methods and varying preferences for the involved vehicles. The mutual evaluation enables a minimum of co-determination for every vehicle.

Furthermore, new CDAS impose new requirements on simulation methods. The high degree of connectivity and interaction of the applications disable a development and later validation without considering the multi-directional influence. The proposed simulation framework allows a flexible modular combination of software components and considers modeling of perception, communication, and controlling of several vehicles in a virtual environment.

A future research topic is the development of ASN.1 specified messages for the decision making process to enable a discussion within the ITS community. Moreover, the specified messages are essential for studies focusing on run time performance of the decentralized process considering communication latency. For this purpose i. a., the German funded project IMAGinE consisting of several OEMs and suppliers is tackling remaining questions along the way to decentralized cooperative maneuvering.

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