IMAGinE

Deliverable D2.5

Specification of Cooperative Maneuver Coordination and System Architecture

Version:	v1.0
Editor:	Volkswagen AG
Project Coordination:	Opel Automobiles GmbH
Due Date:	31.03.2022
Creation date	06.04.2022
Publication:	13.04.2022

Gefördert durch:

Bundesministerium
für Wirtschaft
und Klimaschutz

aufgrund eines Beschlusses
des Deutschen Bundestages

DOCUMENT INFORMATION

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
AQ	Accuracy Quantization
CAM	Cooperative Awareness Message
CMC	Cooperative Maneuver Coordination
CMP	Collaborative Maneuver Protocol
COM	Communication module
CPM	Collective Perception Message
CTRA	Linearized Constant Turn Rate and Acceleration
EKF	Extended Kalman filter
FGW	Framework2Framework gateway
GNSS	Global Navigation Satellite System
GUA	Joint subcontract
HMI	Human Machine Interface
IDMS	IMAGinE Driving Strategy Message
IRS	Intelligent Roadside Station
ITDM	IMAGinE Traffic Distribution Message
KOP	Cooperative maneuver planning and coordination
MCM	Maneuver Coordination Message
MPT	Most Probable Trajectory
RDBMS	Relational database management system
RoI	Region of Interest
ROS	Robot Operating System
StVO	Road traffic regulations
SUPS	Support server
TETTC	Time-Exposed Time-to-Collision
TTC	Time-to-collision
UMF	Cooperative environment model

1 INTRODUCTION

In public road traffic, it can often be observed how road users cooperate with each other. For example, one motorist yields the right of way to another by signaling this with a hand gesture. This type of cooperation is often based on one of two reasons. Either there is no clear regulation on how road users should behave in the current situation and they proactively avoid critical or inefficient situations by cooperating, or the appropriate regulation for the situation results in a road user being unable to act as long as no other road user behaves cooperatively.

This imprecise regulation poses a particular challenge for automated driving. For automated driving, it is necessary to formulate the rules of the road as an exact algorithmic description. Since these rules can be interpreted in different ways, it cannot be assumed that all automated driving vehicles will behave in the same way. Furthermore, it must be assumed that there will always be vehicles that will not drive in an automated manner. Therefore, it is necessary that automated driving vehicles will exhibit cooperative behavior in the future and coordinate their maneuvers with other vehicles.

Within the framework of IMAGinE, various concepts have been developed that enable cooperation between vehicles. These concepts can be used to coordinate maneuvers between any vehicles. No specific degree of automation of the vehicles is assumed. This means that they also allow maneuver coordination between automated, partially automated and manually driven vehicles.

This Deliverable D2.5 describes several maneuver reconciliation concepts in addition to the process defined in D2.1 and jointly tasked in GUA1. Each partner has focused on one of the maneuver reconciliation concepts. Procedures alternative to, complementary to, or extended from GUA1 have been described both in the literature and within IMAGinE in an "addendum" to the GUA1 solicitation and other documents. The IMAGinE system interfaces have therefore been designed to cover the required data exchange of all procedures named in IMAGinE and also to be basically extensible for future procedures. D2.5 describes the basic concepts. The basic implementations of each maneuver planner and coordination concept were verified in a simulation environment in a series of test scenarios for several IMAGinE cooperative functions (proof-of-concept verification). In addition, the common components of the IMAGinE architecture are presented as an overall system and necessary adaptations resulting from the simulation are shown.

2 TECHNICAL FRAMEWORK

2.1 General IMAGinE architecture

For the complex task of IMAGinE, which involves cooperative coordination and automated driving across partners, the IMAGinE partners agreed on some common features in the test systems to reduce complexity. For this purpose, a reference architecture was defined, which includes a partner-specific part, but also a common (cooperative) part. The common reference architecture is shown in the following figure:

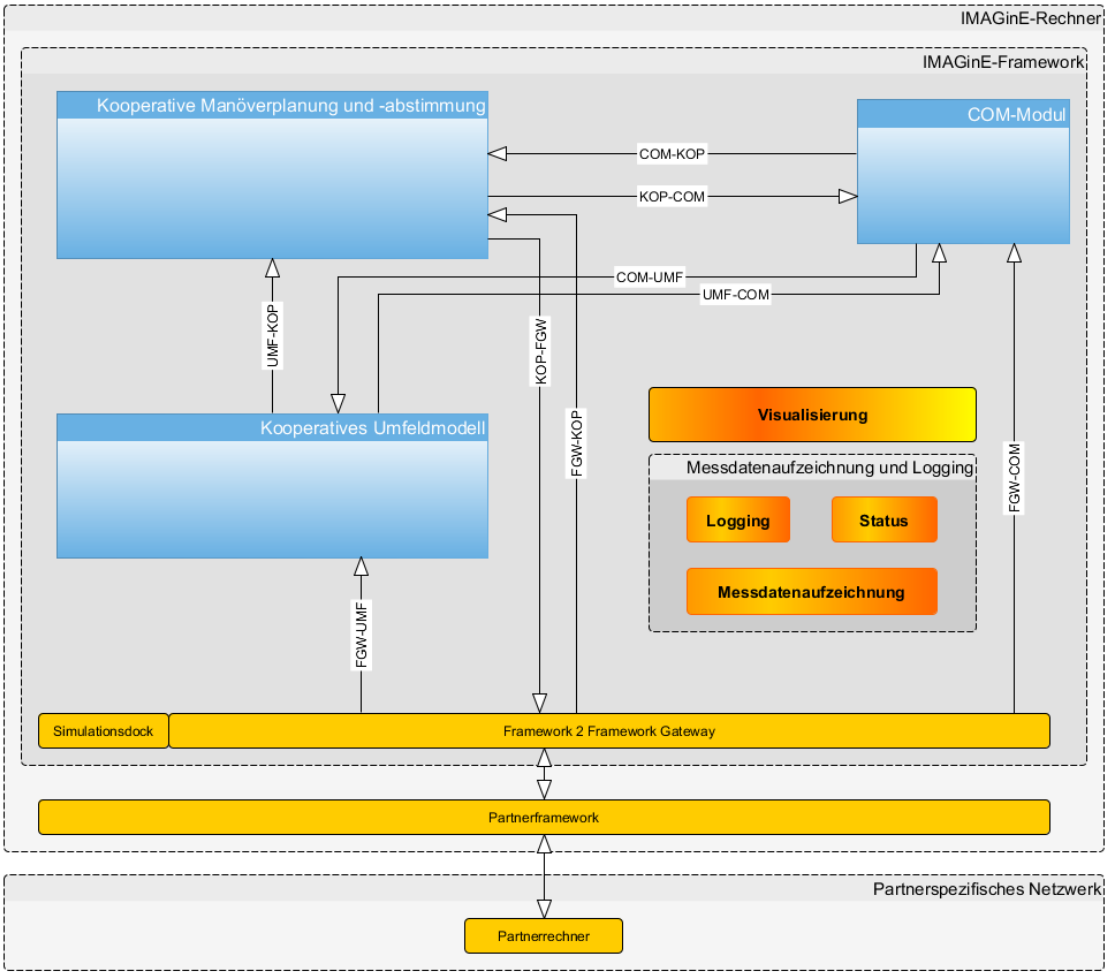

Figure 1: System architecture of the IMAGinE system

The connection to the partner system is done via a Framework2Framework gateway, which was created by each partner on their own to connect their own systems to the cooperative IMAGinE systems. The individual cooperative components can either be implemented by the partners themselves or integrated as jointly implemented software in the partner-specific simulation environments. However, these solutions were the responsibility of the partners themselves, ensuring that the common interfaces were operated correctly, both within their own vehicle and, more importantly, in vehicle-to-vehicle communication.

The modules "Cooperative Environment Model" and "Cooperative Maneuver Planning and Coordination" are software modules developed in joint subcontracts. In order to illuminate the various aspects of cooperative maneuver coordination from as many sides as possible, different types of maneuver coordination have emerged in the course of the project, which have been contributed by different partners. As a result, deviations from the reference architecture occur among the different partners. The procedures for investigating the different aspects of maneuver coordination are described in the chapter "Description Concept of IMAGinE Cooperative Maneuver Coordination".

2.2 Cooperative environment model

IMAGinE is researching the realization of cooperative functions. For this purpose, the module "Cooperative Maneuver Planning and Coordination" (KOP) was developed and tested in the vehicle. The functions such as merging, turning, etc. plan trajectories so that cooperation of all necessary vehicles can take place. To plan these trajectories, information about objects in the environment is necessary. In IMAGinE, these objects are stored in an environment model. The information contained in this environment model can come from multiple sources, such as onboard sensors as well as V2X communications. This is called collective perception. In IMAGinE, this V2X interface is called the communication module (COM). The following figure shows the structure of the IMAGinE computer as well as the developed modules.

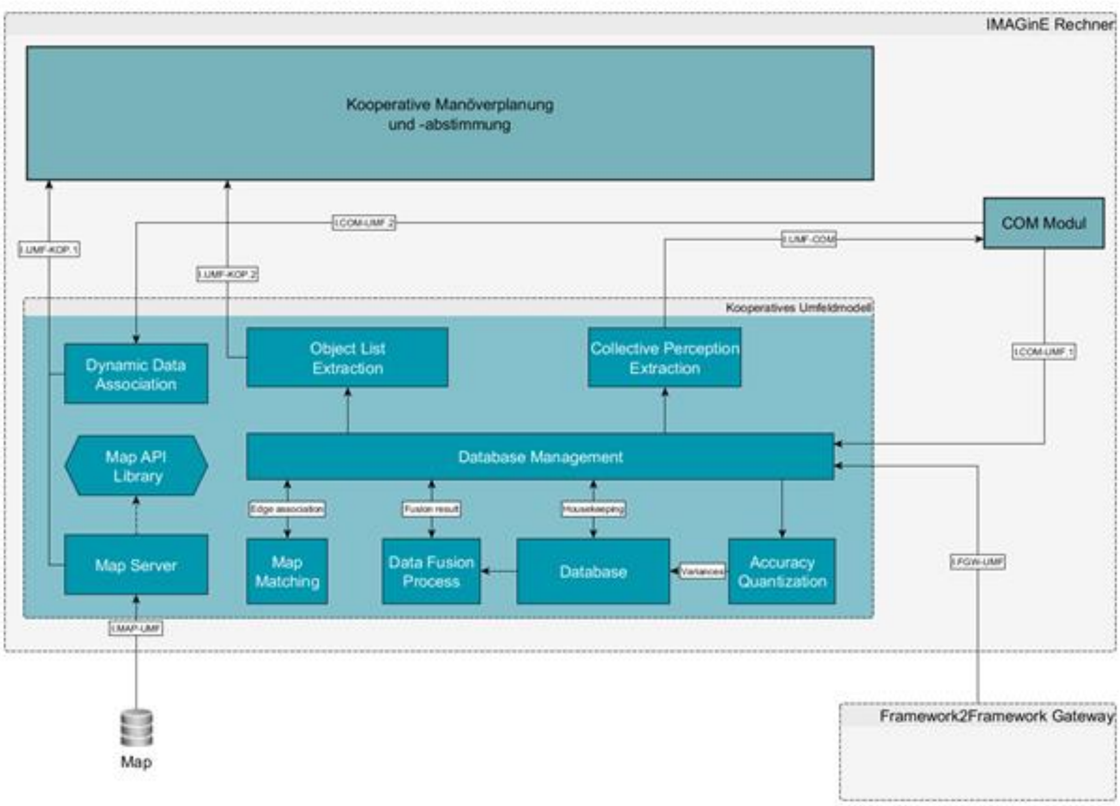

Figure 2: System architecture cooperative environment model

The module "Cooperative Environment Model" (UMF) forms the information basis for the KOP module. Two interfaces have been defined for this, UMF-KOP.1 and UMF-KOP.2.

The UMF module uses, among other things, information from the CPM and CAM, which it receives from other vehicles via the COM and with which it communicates via the UMF-COM and COM-UMF interfaces. In addition, it receives messages from the partner-specific system via the FGW-UMF interface.

The concept of the Cooperative Environment Model is based on the so-called object list fusion approach. This fuses the local object list with the V2X objects to form a global object list. The local object list is the result of the partner-specific data fusion of the vehicle's own sensor objects.

Object List Fusion Approach

Each cooperative vehicle sends information about itself and its detected, surrounding vehicles via the V2X interface by means of the CAM and CPM. The messages are received by the COM module and provided to the UMF. The information is already available here fused as an object list in the messages. The object lists are consolidated with all other received as well as self-detected objects to a global object list. So if there are no V2X vehicles in transmission range and therefore no V2X messages are received, the local and global object list of the UMF is exactly identical.

When a V2X message is received, the information it contains is used to improve or extend the information of the Cooperative Environment Model. For example, information about the objects managed by the environment model is updated or even specified by new incoming information and, if necessary, new objects are added or objects that no longer exist are removed.

For the fusion and the provision of the global object list, it is also necessary that the environment model transforms the coordinates and represents them relative to the defined reference point of the ego vehicle. The reference point for the ego coordinate system is the center of the front bumper (FMID) for IMAGinE vehicles.

Data Fusion

The environment model merges all information. The data from different vehicle sensors and from V2X are used and merged into a common (global) object list. The sensor data is assigned to the objects for this purpose; the totality of the sensor data of an object is referred to as a track.

In each step, it must be checked for all object information from the sources whether this new information can be assigned to known objects or whether a new object must be created. This is done by the so-called gating. In the subsequent association, an unambiguous assignment of the measured values to the objects is achieved.

To keep the variance of the measurement data as small as possible, an Extended Kalman filter is used. For the object state of the Extended Kalman filter, position, velocity, acceleration, yaw angle and yaw rate are considered. The prediction of the object state is done by the constant-turn/constant-velocity model. For the fusion of the measurement data from different sources, they must also be predicted or retrodicted to the same point in time.

For fusion, it is necessary that the sensor measurements are comparable. For this, the uncertainties of the measurements must be used in a uniform format. Since the manufacturers of the sensors do not want to disclose the uncertainties, a quantization of the covariances of the sensors is performed. This normalization of the covariances is done in the component "Accuracy Quantization" (AQ).

Data management

The environment model must hold object data for maneuver planning and collective perception. For this purpose, the data structures are stored in the main memory of the respective computer, which usually provides performance advantages over storage in a relational database management system (RDBMS) with persistence mechanisms. Data management, including a housekeeping process, is part of data storage. This has the task of updating, creating or, if necessary, removing the object data.

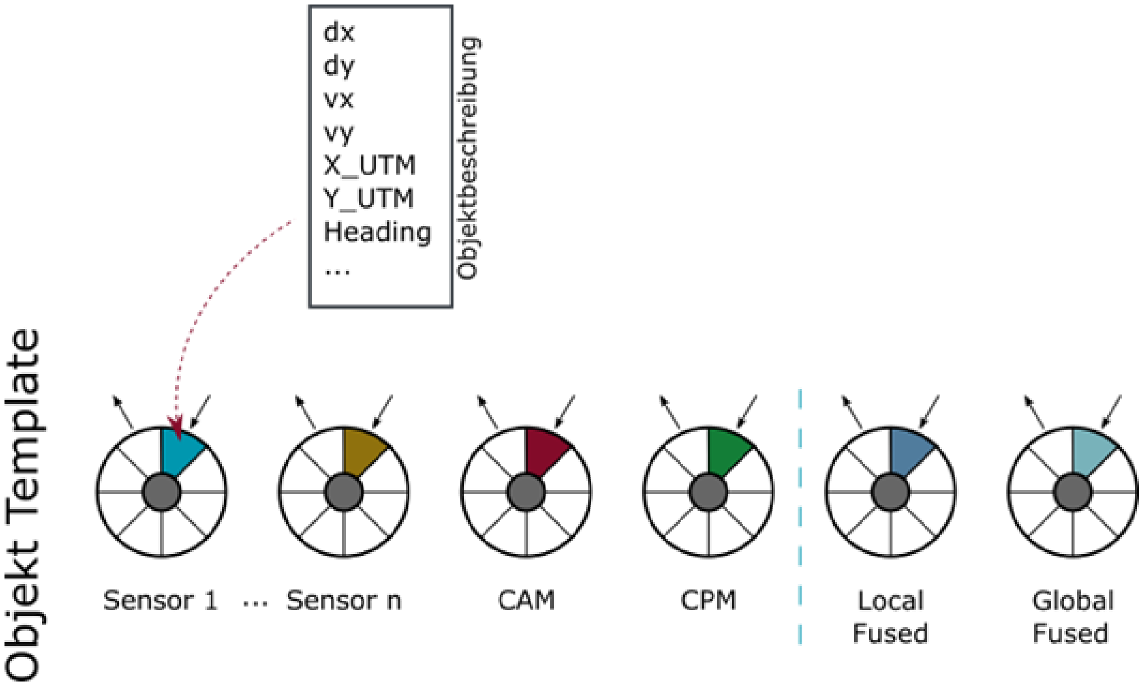

Figure 3: Representation of the database management system

For each of the objects not only the current object state is stored, but also the information from the input sources, i.e. sensors or CAM or CPM messages. There is also a storage of the local and the global fused state. The locally fused state does not contain the values from V2X messages. The use of V2X messages to extend the environment model is called Collective Perception. To enable better analysis, the data is stored in a circular buffer.

Map matching

For maneuver planning, it is necessary to know the lane on which the vehicle is located. For this purpose, a map matching function was implemented, which assigns the absolute positions of all objects to exactly one lane.

Digital map / road model

For the planning and coordination of maneuvers as well as for map matching, it is necessary to have an abstract understanding of the road space. Therefore, a representation form for maps was developed in IMAGinE that fulfills the requirements of the six functions. For this road model, there is a map server that extracts and converts map data from other formats, e.g. OpenDrive, within a defined perimeter. The maps can then be used by all other components via ROS topics. In addition, there is an API through which certain functionalities, such as map matching, can be used.

In addition, there is also the possibility that dynamic road data communicated by the support server, e.g. road closures, are processed by the map server and dynamically associated in the road model. Frenet coordinates are used as the basis for the road model in order to be able to cooperatively plan trajectories.

Data extraction components

For the global and local object list there is one component each, which extracts these lists from the ring buffers and makes them available to the other modules via the corresponding topics. These lists can be sorted by distance to the ego vehicle and by an object fitness calculated from the object reliability, which is based on the covariances.

2.3 Visualization

A visualization was developed for RViz that can display the ego vehicle, map data, the objects from the environment model and trajectories. Additionally, there is a display that shows values of the objects. The following figure shows a screenshot of the visualization.

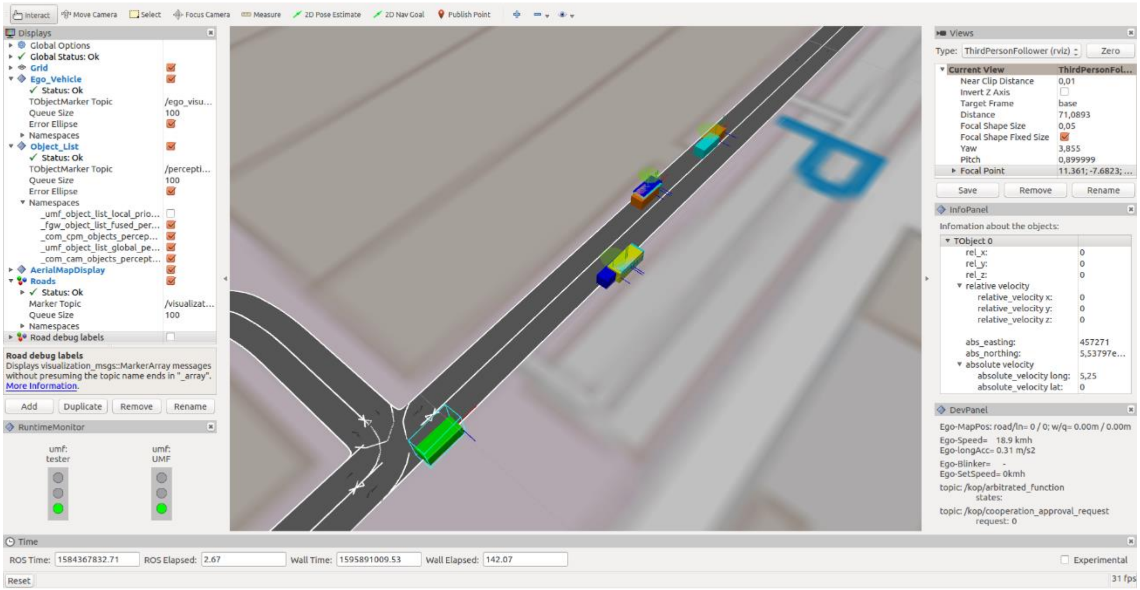

Figure 4: IMAGinE Environment Visualization

2.4 Communication module

The communication module (COM module) fulfills the task of transmitting the required data between the individual vehicles and infrastructure stations. The hardware used for this is the waveBEE devices, which have been installed in the vehicles and the infrastructure involved. The waveBEEs support either the ITS-G5 / 802.11p standard or the exchange via LTE and a GeoServer on the Internet. The communication module represents the interface between the data within the IMAGinE system and the waveBEE. The individual data exchanged are described in more detail below.

CAM (Cooperative Awareness Message)

The CAM messages are used to inform other communication participants about one's own situation. In addition to the GNSS position, other information such as the current orientation, speed and acceleration as well as static data about one's own vehicle, e.g. dimensions, are also transmitted. Since both the position information from the GNSS sensor and the other movement data are recorded internally in the vehicle, this message has a high degree of accuracy with regard to the own vehicle data.

The communication module extracts the required data from the various messages available in the IMAGinE system and transfers them to the waveBEE device for transmission to other vehicles using the waveBEE API. Incoming CAM messages from other vehicles are already collected on the waveBEE device. The collected data is then converted into IMAGinE's internal format by the communication module and forwarded to the IMAGinE system as an object list. Thus, each vehicle can receive and evaluate the position and movement data of the other communication participants.

CPM (Collective Perception Message)

The CPM messages are used for the exchange of local sensor data beyond vehicle sensor boundaries and are used to extend the own environment model. For this purpose, the result object list of the data fusion of local sensor data is sent from each vehicle to the other communication participants. This list contains position, velocity, acceleration and dimensions relative to the sending vehicle as well as its own position and motion data. Not all of this data from each detected object needs to be populated, as not all can be detected by each vehicle sensor. In order for receivers of CPMs to estimate the accuracy of the detected data, the transmission of variances for individual values is also necessary.

The communication module reads the result object list from the IMAGinE system, re-encodes it into the format provided by the waveBEE API for CPMs, and then sends it to other vehicles through the CPM service of the waveBEE device. CPM messages received from other vehicles are individually re-encoded into internal output object lists and forwarded to the IMAGinE system, where they can then be used by the environment model to generate a cross-vehicle fusion.

MCM (Maneuver Coordination Message)

The MCM messages are used to exchange the various types of trajectories required for cooperative coordination between vehicles. In addition to the vehicle identifier, they mainly contain reference, demand and alternative trajectories of the sending vehicle.

For this message type, the communication module itself fulfills the encoding of the messages in ASN.1 and sends them between the vehicles using the generic ASN service of waveBEE. The incoming MCM messages are decoded and forwarded to the IMAGinE system for further processing. Similarly, the IMAGinE Traffic Distribution Message (ITDM) and IMAGinE Driving Strategy Message (IDSM) message types are used by some procedures developed in IMAGinE for cooperative coordination at the driving strategy level.

ITDM (IMAGinE Traffic Distribution Message)

The ITDM messages are used to realize the cooperative strategic traffic distribution. On the one hand, they are used to publish a traffic distribution desired by the traffic center, and at the same time they are used to exchange necessary data between the vehicles that are required for the cooperation process.

For this message type, the communication module itself fulfills the encoding of the messages in ASN.1 and sends them between the vehicles using the generic ASN service of waveBEE. The incoming ITDM messages are decoded and forwarded to the IMAGinE system for further processing.

IDSM (IMAGinE Driving Strategy Message)

The IDSM messages are generic messages that is used for strategic voting across distributed state machines. The IDSM messages provide the possibility for vehicles to coordinate synchronously.

3 DESCRIPTION OF COOPERATIVE MANEUVER COORDINATION CONCEPTS

3.1 Overview of partner-specific procedures for examining aspects of maneuver coordination

Within the IMAGinE project, several concepts for cooperative maneuver coordination have been introduced by the partners, which are summarized in the following overview. The concepts were classified into the following categories according to their essential characteristics. In particular, the distinction between *implicit* and *explicit* characteristics must be taken into account (see below).

- **Concept:** Short name of the concept
- **Project partner:** Project partner who brought this concept into IMAGinE.
- **Characteristics:** Overarching features of the concept on the process of negotiation in a cooperation (implicit and/or explicit), on its course (continuous and/or event-driven), and on its control (centralized and/or decentralized).
  - *Explicit*: Explicit cooperation takes place with cooperation partners who explicitly, i.e. unambiguously and unequivocally, promise their willingness to cooperate to the cooperation partner in need of cooperation and, if necessary, also explicitly revoke their willingness to cooperate before the cooperation is concluded. This must be done by exchanging information that is unambiguous for the recipient, such as the sender's willingness to cooperate and signals that can be clearly assigned to the cooperation partners concerned. It is also possible to derive information from several signals if the uniqueness of the derivation is permanently maintained for all recipients even under different conditions (e.g., card use). A request for cooperation is explicit if it unambiguously identifies specific receivers whose willingness to cooperate is being requested. Explicit cooperation typically includes a coordination phase and an implementation phase.
  - *implicit:* In the case of implicit coordination, an exchange of messages takes place between the cooperation partners from which the cooperation partners themselves can infer the willingness of other partners to cooperate at their own discretion, for example by evaluating the situation themselves and applying any rules, without the prerequisites of explicit cooperation being guaranteed. Each participant takes this information into account in his or her further planning and, if necessary, adjusts his or her intentions in order to achieve a more favorable result across the board. Only from the reactions of other participants can conclusions be drawn about their compliance with their own wishes.

  - *continuous*: Possible cooperation partners send out messages in support of possible cooperation on a cyclical basis, even if they themselves are not currently requesting cooperation or do not wish to grant certain cooperation.
  - *event-driven*: collaboration partners send out messages to support or execute collaborations only when needed.
  - *central:* An excellent, central authority ("master") decides - at least in certain periods - on the implementation and steering of collaborations. Other cooperation partners provide information and feedback.
  - *Decentralized*: Collaborations are started, carried out and terminated on an equal footing without an excellent, controlling authority ("peer-to-peer").
- **Planning principle:** Elements of the concept on the basis of which a cooperative maneuver is planned (intentions, relations and/or situations) and corresponding planning level (strategic, tactical and/or operational). For example, intentions can be executed in the form of trajectories.
- **Coordination principle:** concept-own trigger for cooperation (conflict and/or other event) as well as procedure for finding a cooperative solution - for all partners involved in the maneuver, with insignificant consideration of the ego-vehicle, or only for the ego-vehicle (global and/or local).
- **Air interface**: V2X message used by the concept (MCM, IDSM, ITDM and/or others) and its relevant content (trajectories, session states, distribution options and/or others).
- **Driving function:** Driving function in IMAGinE prototypically implemented with the concept.

Table 1: Overview of partner-specific concepts in IMAGinE

Concept	Project partner	Characteristic	Planning principle	Voting principle	Air interface	Drive function
IMAGinE2018	Robert Bosch GmbHContinental Teves AG & Co. ohG	implicitcontinuousde-central	Intentions	Conflict	MCM	F1F5
			tacticaloperational	globallocal	*1* Reference trajectory *0..n* Demand trajectories *0..m* Alternative trajectories (with costs)	
pre-IMAGinE2015	Volkswagen AG	implicitcontinuous decentralized	Intentions	Conflict	MCM	F1F3
			tacticaloperational	globallocal	*1* Plan trajectory *0..1* Desired trajectories	
OpelCore2018/19	Opel Automobiles Ltd.	implicitcontinuousde-central	Intentions	Conflict	MCM	F1
			tacticaloperational	local	*1* Trajectory (reference/demand/supply)	
AltTraj2018	Opel Automobiles Ltd.	implicitcontinuousde-central	Intentions	Conflict other event	MCM	
			tacticaloperational	global	*1* ideal trajectory *0..1* hesitation trajectories	
Targets2019	Opel Automobiles Ltd.	implicitcontinuousde-central	Intentions	Conflict	other	
			strategic tactical operational	global	*1* long-term goal *1..n* medium-term goals *n..m* short-term goals	

Concept	Project partner	Characteristic	Planning principle	Voting principle	Air interface	Drive function
Bbasic2019	BMW AG	expliciteventcontrol-leddecentral	Intentions Relations	other event	MCM	F1
			tactical	globallocal	*n* attributes *m* relations	
BBB2019	BMW AG	explicitcontinuousde-central	RelationsIntentions	Conflict other event	MCM	F1
			tactical	globallocal	*n* attributes *m* relations *k* ranges of motion	
Collaborative Maneuver Protocol (CMP)	Mercedes-Benz AG/DCAITI	explicitCentral synchronizedState machine	Relations (roles)	Change of state	IDSM	F2
			strategic tactical	globallocal	*1* Session state	
Truck-LongControl 2019	MAN Truck & Bus SE	implicitcontinuousde-central	Intentions	Conflict	MCM	F2
			strategic tactical	globallocal	*1* Plan trajectory *0..1* Desired trajectories	
Truck-Overta-king2017/18	MAN Truck & Bus SE	explicitdecentral	Relations (roles)	other event	IDSM	F6
			strategic tactical	globallocal	*1* Session state	
Traffic Distribution (ITDM)	The Federal Mo-torway Ltd.	implicit central	Situations	other event	ITDM	F4
			strategic	global	*n* Distribution options	

3.2 Cooperation concept IMAGinE 2018

The following chapter describes the concept as it was implemented in GUA1 and used for the final in-vehicle demonstration.

3.2.1 Basic concept

3.2.1.1 Assumptions

Maneuver coordination requires the exchange of messages between locally adjacent vehicles. It is assumed that the communication technology used is capable of transmitting messages from one vehicle to all vehicles within a radius of several hundred meters by radio. The minimum range required for the concept has yet to be determined in the course of further work. The maneuver coordination concept presented here is based on the following assumptions.

The concept is based on the exchange of trajectories. It is assumed that the trajectories have a time length between 1 and 30 seconds. For shorter trajectories, maneuver coordination does not make much sense because the coordination process itself takes some time. Longer maneuvers cannot be planned with enough certainty using a trajectory, so coordination based on trajectories does not seem to make much sense. The exact time constraints still have to be determined in the further course of the project.

In order to be able to recognize when maneuver coordination is necessary and to determine which road user takes which role in the coordination, right-of-way rules are necessary. In Germany, for example, these are defined by the StVO.

It is assumed that the vehicles have incomplete knowledge and that this knowledge cannot be fully established even by means of communication. Therefore, the concept must be designed in such a way that each vehicle involved in the coordination makes its own decisions and the process of coordination provides for appropriate freedoms.

The future cannot be predicted precisely. The trajectories exchanged here are predictions made on the basis of model assumptions. Despite everything, unforeseen events can occur that render these predictions invalid.

Maneuver coordination is decentralized, meaning there is no central authority controlling cooperative maneuver coordination.

3.2.1.2 Transmitted information

The following information is exchanged between the vehicles and is explained in more detail in the following subchapter:

- The reference trajectory of the vehicle
- A number M (with M ≥ 0) of demand trajectories.
- A number N (with N ≥ 0) of alternative trajectories.

- A relative cost value C (with $-1 \leq C \leq 1$) for each transmitted trajectory. The relative cost values of the trajectories are determined as follows:
  - The reference trajectory has the cost value C_0 in the interval $-1 \leq C_0 \leq 1$
  - Demand trajectories have a cost value $-1 \leq C < C_0$
  - Alternative trajectories have a cost value $C_0 < C \leq 1$
- Optional: additional information for each trajectory:
  - A categorization: e.g. cooperation offer / emergency trajectory / deployment trajectory / etc.
    - As a concept extension: the category "driving proposal" to send trajectories for other vehicles
  - A list of V2X Ids of other vehicles to which the trajectory refers with its categorization.
  - Multiple categories can also be specified, e.g. to show a cooperation offer and a cooperation rejection at the same time. Each category has optionally its list of V2X-Ids.
- Optional: degree of automation:
  - *could theoretically be useful to estimate the "quality" of both trajectories and granted commitments. Was not used in the implementation.*
- Optional: Negotiation timeout:
  - *could theoretically be useful in case there are several possible cooperation partners. Was not used in the implementation.*

For the coding of all these data for transmission, the MCM (Maneuver Coordination Message) developed within the project is used. Trajectories are defined there starting from an absolute starting position (GNSS) in a Frenet representation. The Frenet system follows the center of the respective lane. Lane changes or driving over intersections mean changes of the Frenet system and are transmitted as a relative description. The spatial and temporal movement within a Frenet system is specified by polynomials.

3.2.1.3 Definition of the signals

3.2.1.3.1 Reference trajectory

- The trajectory that the vehicle is currently following and which is the setpoint for the motion controller / driver.
- Reference trajectories should be free of conflict/ collision with each other.
- If conflicts/collisions occur, they are resolved in accordance with the StVO. A conflict must be resolved by the vehicle that has the lower priority according to the StVO. The vehicle

with priority may therefore continue to send its conflicting trajectory. If the conflict remains, then it indicates a different understanding of the situation and **both** vehicles must resolve the conflict, e.g. by decelerating.

3.2.1.3.2 Alternative trajectories

- A trajectory that is more expensive than the reference trajectory, but which the vehicle would still be willing to drive if necessary. "If applicable" here means "subject to reservation", i.e. before an alternative trajectory can become the reference trajectory, the driver may still have to give his consent, or an evaluation of the resulting overall situation may still take place, whereby a final check may be made as to whether one's own additional costs are offset by a sufficient benefit (from a local perspective) for the other vehicles.
- Since an alternative trajectory should be a realistic cooperation offer, it should be free of conflict with other reference trajectories. Unlike the reference trajectories, this is not mandatory, because alternative trajectories are part of the negotiation process.

3.2.1.3.3 Demand trajectories

- A trajectory that better fulfills the desired destination, thus is more favorable than the reference trajectory.
- Conflicting with other trajectories. "Other trajectories" here are exclusively foreign reference trajectories. If these are too short, e.g. due to a different planning horizon, and there are only conflicts in the internal extrapolation, no demand trajectories may be sent.

The following figure illustrates the different trajectories.

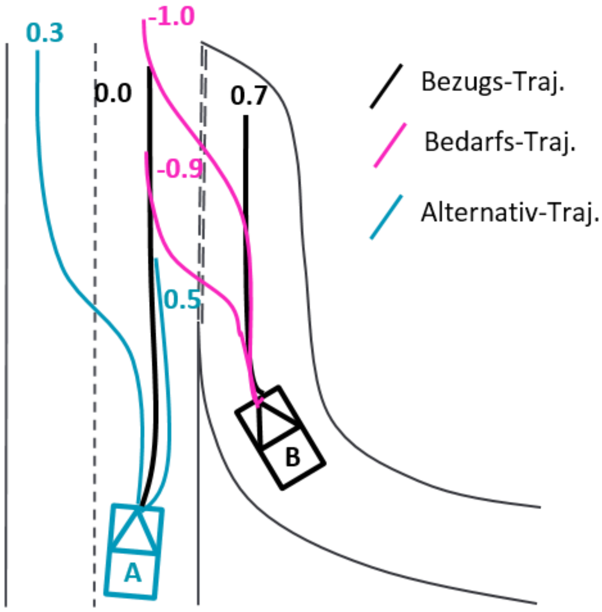

Figure 5: The priority vehicle A offers alternative trajectories. The subordinate vehicle B sends demand trajectories. The reference trajectories are collision-free.

3.2.1.3.4 Categories

As optional information it is foreseen that each trajectory can be provided with additional category information. This category information can be helpful for the consideration of the trajectory in the maneuver planning in the other vehicles. In principle, any type of trajectory can be provided with category information.

- **Emergency trajectory**: If the vehicle follows this trajectory, then it is in a technical (e.g. tire blowout) or situational emergency (e.g. child runs onto roadway), i.e. it will not be able to follow normal traffic rules (e.g. stopping on highway) or poses a potential hazard to other vehicle (by braking/steering hard).
- **Cooperation offer:** This trajectory represents an offer to other vehicles to enable their demand. The vehicles concerned can be addressed directly via another optional field - the V2X ID. Likewise, a field is provided to address a specific (demand) trajectory of a third-party vehicle, thus limiting the offer to a specific expressed demand.
- **Cooperation rejection:** This trajectory represents a rejection of a cooperation request from another vehicle that the latter has expressed by means of demand trajectories. The vehicles concerned can be addressed directly via another optional field - the V2X ID. Likewise, a field is provided to address specific (demand) trajectories of another vehicle, thus limiting the rejection to a specific expressed demand.
- **Emergency vehicle**: On this trajectory, the vehicle has special priority because it is in operation. This can supplement the information from the CAM about "Emergency vehicles in operation".
- **Driving suggestion**: This category can be used in conjunction with the V2X ID field to send trajectories as maneuver suggestions for other vehicles. This can be used, for example, by emergency vehicles that want to suggest to other vehicles how an emergency lane could be formed. Or also by an infrastructure unit at intersections to optimize traffic flow. Driving suggestions are non-binding. This category should be seen as a research topic, just as other categories could be used for future expansion.

3.2.1.3.5 Cost values for the cooperation

The cost values reflect whether and to what extent a vehicle on the specified trajectory benefits from cooperation concessions made by others or incurs additional effort itself because it enables others to maneuver while foregoing its own advantage. To enable a common understanding across the board, the costs are normalized to an interval from -1 to 1. "-1" represents trajectories which - considering the situation - represent the best possible result for the own vehicle that can be achieved by cooperation. On the other hand, "1" represents trajectories that contain the maximum concession to others to realize their maneuvers.

Within the vehicle, the cooperation costs of trajectories can be determined by the costs of two boundary trajectories, which - from the vehicle's point of view - each correspond to the description of one of the two interval boundaries above. The other trajectories including the reference trajectory are sorted accordingly, e.g. by setting their internal costs determined with the local cost function in relation to the internal costs of the two boundary trajectories.

The determination of the two boundary trajectories can be done with sufficient accuracy as follows: For the best possible trajectory (i.e., lower boundary trajectory), one determines an ego trajectory in an environment in which all other vehicles capable of cooperation are neglected, since in the best case they enable EVERY cooperation request (driving physics is ignored). Determining the upper bound trajectory, which reflects what concessions to trajectory enabling others are still acceptable, is less clear. For example, the following approaches are conceivable, all of which are sufficient in terms of accuracy for the concept, but in ascending order may lead to a more globally optimal result.

- A flat internal vehicle cost limit is defined: The trajectory is then selected whose costs are, for example, 20% above that of an internal reference cost value. The internal reference cost can be determined e.g. from the reference trajectory, or the best possible trajectory, or preferably from a combination of both. In IMAGinE, the first has been implemented.
- The above cost limit will be adjusted depending on the maneuver/situation.
- In the case of manual driving, the cost limit can be learned from driver behavior during cooperation requests and would then be adaptive.

The exactness of the two boundaries, or their cost, is not so important as the basic tendency, or relation, between them. The sending of the two boundary trajectories is not absolutely necessary, but can be omitted in favor of other demand / alternative trajectories (which the vehicle assumes solve a cooperative situation better overall).

3.2.2 Reconciliation concept

The concept is based on two fundamentals. First, each vehicle permanently sends its reference trajectory to inform the other vehicles how it will move for the next few seconds - as long as its situation does not change. In principle, reference trajectories do not conflict with each other - any conflict that arises must be resolved by the vehicle with the lowest priority according to traffic rules by adjusting its reference trajectory. Second, each vehicle permanently sends one or more alternative trajectories, which give other vehicles an impression of the extent to which they can count on support in order to improve their own situation through the cooperation of others.

When vehicles come to the realization that they need support from others, they communicate this by sending one or more demand trajectories. To determine the trajectories of need, they use the scope shown by the alternative trajectories. Vehicles affected by the cooperation request - i.e., their own reference trajectory conflicts with one of the received demand trajectories - evaluate internally whether the resulting restrictions are acceptable to them and, if necessary, adjust their reference trajectory accordingly. The adjustment of the reference trajectory is the implicit signal for the requesting vehicle that the cooperation request has been accepted and it can now place its own reference trajectory in the freed-up maneuver space.

If no alternative trajectories are available, or if the existing ones do not provide sufficient margin to solve the situation, the vehicle can also send a demand trajectory that it considers to be better, based on a self-estimated margin. Such demand trajectories may have a lower chance of being accepted by other vehicles, since it may be difficult and costly to determine its own margin. To avoid this situation and also to keep the computational load in the vehicles low, it is important that each vehicle sends at least one alternative trajectory as an informative cooperation offer in addition to its reference trajectory. If several maneuvers with similar marginal costs are possible (on highway: braking or lane change), it is helpful to send an alternative trajectory for each maneuver.

In order to be able to determine the cooperation costs of their own trajectory and thus to inform the other vehicles about the degree of their willingness or need to cooperate, the vehicles permanently calculate their maximum gain from cooperation and maximum acceptable effort for cooperation, e.g. by determining their upper and lower boundary trajectories.

3.3 Concept presentation Volkswagen

3.3.1 Assumptions and requirements

Volkswagen's approach is based on the idea of performing all coordination solely through the exchange of planned and desired trajectories (see Figure 6). Cooperating vehicles are able to communicate via V2X as well as to perform maneuvers automatically. This assumption is based on the thesis (yet to be proven) that such a concept works for different levels of automation as well as for different levels of V2X equipment.

It is assumed here that rules (e.g. the StVO) are implemented in the vehicles, which the vehicles take into account when planning their own planned and desired trajectories (see following paragraphs).

It is also assumed that this approach is generic, i.e. that it can be used for all drivable maneuvers. It is taken into account that the vehicles involved calculate their planning on a different knowledge base in each case. Due to this, this approach does not initially consider safety-critical functions. The goal of this approach is therefore primarily to improve the prediction of the driving behavior of dynamic objects in their own area of relevance.

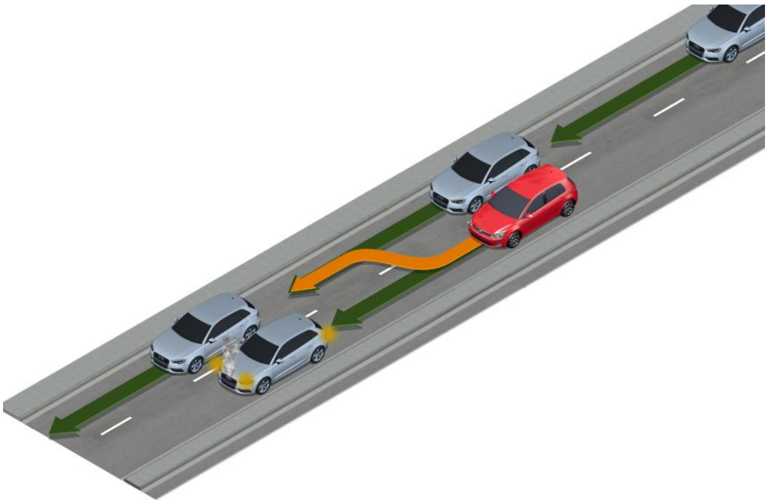

Figure 6: Volkswagen's concept for maneuver coordination based on the exchange of plan trajectories (green) and wish trajectories (yellow).

3.3.2 Trajectories

The message for the concept proposed here involves the continuous computation of planned and (optionally) desired trajectories.

The plan trajectory (see Figure 6, green arrow) describes the predicted path-time line based on the information currently available to the vehicle (e.g. current speed, current steering angle, current acceleration, navigation route planning). By definition, plan trajectories are always collision-free with each other. If, on the other hand, a vehicle changes its current driving style, for example by braking, its plan trajectory also changes. This can mean that the previous solution for a plan trajectory may no longer be maintained, as it would no longer be collision-free with the plan trajectory of another vehicle (see Figure 7), which is prohibited by definition.

Figure 7: Plan trajectory is no longer allowed because it is no longer collision-free. Instead, a collision-free solution must be found.

It is therefore necessary that at least one of the two vehicles adjusts its trajectory. One possible adjustment would be a lane change of the own, red vehicle, in order to make the trajectories collision-free again ergo to avoid an accident.

This so-called desired trajectory (see Figure 8) results from a desired deviation from the plan trajectory. In contrast to the plan trajectory, however, the desired trajectory ignores the plan trajectories of other vehicles and thus need not be free of conflicts. The desire trajectory thus represents a cooperation request: In this example, it represents the desire for a lane change, which, however, cannot be implemented without the cooperation of the vehicles in the adjacent lane. This is shown by the conflict of the desired trajectory (yellow) with the planned trajectories (green) of the other vehicles.

The cooperation request in the form of the desired trajectory is addressed to all vehicles whose plan trajectories conflict with the desired trajectory. If these vehicles were to adjust their plan trajectories accordingly, freedom from conflict could thus be restored.

Figure 8: Desired trajectory (yellow) in response to the invalid plan trajectories because they are no longer conflict-free. The reason is that an adjustment of the plan trajectory would result in an increase in costs; the desire trajectory would represent a more cost-effective alternative (if it were accepted).

It is now up to the willingness of this vehicle to cooperate whether it agrees to the request of the red vehicle and adjusts its trajectory or not. The willingness to cooperate depends, among other things, on the individual cost consideration (technically implemented in the form of a cost function) of the vehicle. If this is acceptable, the vehicle will adjust its plan trajectory so that it is free of conflict with the desired trajectory of the red vehicle. As soon as this is the case, the desired trajectory becomes a planned trajectory and the red vehicle can change lanes.

3.3.3 Cost function

Provided that the desired trajectory can be implemented as intended, this represents the better alternative to the original planned trajectory from the point of view of the vehicle itself. "Better" here always means lower costs. The costs result from a consideration of parameters relating to driving dynamics, desired driving comfort, driving safety and target achievement (the so-called cost function of the ego vehicle).

Another criterion for the cost function (and consequently the willingness to cooperate) is also the impairment of other road users and the associated risk for oneself. For example, braking hard may be cooperative (such as the cooperation-giving vehicle in Figure 6) because it allows the other vehicle to change lanes. At the same time, however, this creates a conflict with the trajectory of the following vehicle.

On the one hand, the lane of the red vehicle in Figure 6 is blocked, which argues for allowing it to change lanes. On the other hand, braking too hard also endangers the traffic following behind. The decision for or against cooperation therefore also depends on the consideration of the environment, which in turn is stored in the vehicle's own environment model.

3.3.4 Resulting reconciliation concept

The reconciliation concept resulting from the above considerations is now summarized as follows:

1. The plan trajectories of the vehicles are available and are always conflict-free.
2. The need for cooperation is communicated in the form of a desire trajectory.
3. The cooperation partner reviews the request with regard to its own criteria for willingness to cooperate.
4. In the case of cooperation, the vehicle then adapts its own plan trajectory to the desired trajectory of the other vehicle.
5. The desired trajectory is now conflict-free and thus becomes the planned trajectory. The red vehicle can change lanes.

The concept is to regularly regenerate and send the plan and wish trajectories, for example at a frequency between 2 and 10 Hz in accordance with the criteria that were also applied for the Cooperative Awareness Message. Since the relevance area is local, a communication technology that supports local broadcast, such as ITS G5, is also suitable for this purpose.

3.3.5 Functionality of the Cooperative Maneuver Planner

In the following, the functionality of Volkswagen's partner-specific cooperative maneuver planner will be described, which is based on the above coordination concept. Here, a cooperative threading process on a highway is used as an exemplary situation (F1). As shown above, the Volkswagen maneuver planner works cost-based. Specifically, the maneuver planner continuously calculates a large number of drivable trajectories in the course of a planning cycle, weights them with a cost function, and selects the most favorable, collision-free trajectory for its planning in each case ("plan trajectory"). For the realization of cooperative maneuvers, up to three preliminary, so-called "interim trajectories" are stored from the set of drivable trajectories in each planning cycle:

- The most favorable interim trajectory, which is absolutely **collision-free** (I-AK).

- The most favorable interim trajectory that is **collision-free** with other plan trajectories while ignoring extraneous desired trajectories (I-PK).
  - *is only stored if it differs from I-AK*
- The most favorable interim trajectory that ignores extraneous plan or desired trajectories and is therefore not **collision free** (I-NK).
  - *is only stored if it differs from I-AK*

In a non-cooperative situation, i.e., when no desired or planned trajectories collide with desired or planned trajectories of other road users, only the interim trajectory I-AK is stored by a planner, since the other possible interim trajectories do not differ from I-AK. Such a situation is shown in Figure 9. The solid line prevents the merging vehicle V01 from calculating a trajectory entering the highway. Accordingly, only the interim trajectory I-AK exists for both vehicle V01 and vehicle V02, which is on the freeway, at time t_1, so they are used as plan trajectories (P-V01 and P-V02, respectively) in the planning cycle (shown in $t_{1.2}$).

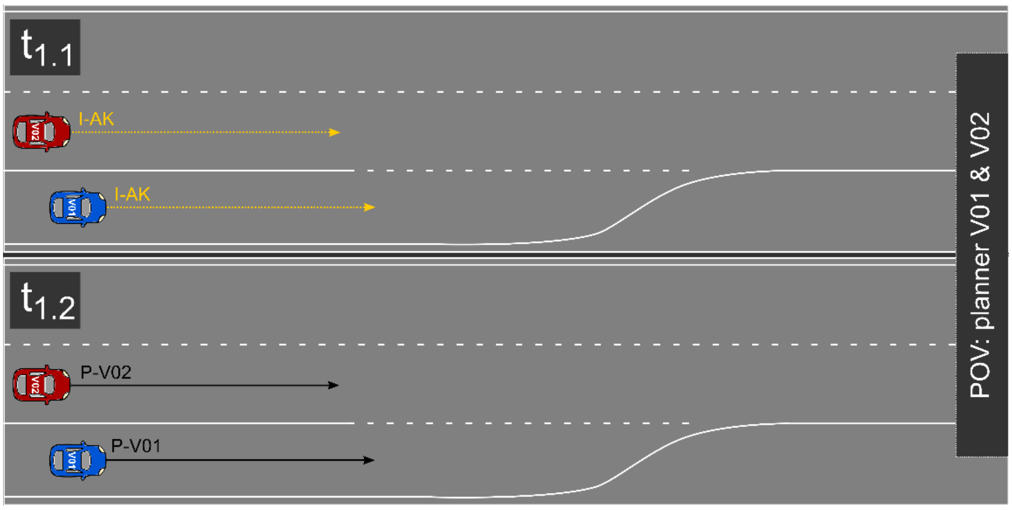

Figure 9: Illustration of a planning cycle for V01 and V02 in which there are no collisions with planned and desired trajectories of the other vehicle.

In a later planning cycle (t_2), V01 is at a position where threading is allowed according to the road traffic regulations. Nevertheless, in this situation V01 selects braking on the on-ramp lane as the most favorable I-AK trajectory, since all other drivable trajectories collide with V02's plan trajectory (P-V02) (cf. Figure 10). In addition, V01 stores the interim trajectory I-NK, which does not have to be collision-free with the plan trajectory of other road users. In the example shown, this represents a threading process onto the highway, since threading at this point is cheaper than braking on the threading lane according to the cost function stored in the planner. However, in order for this interim trajectory to be run in the near future, successful cooperation with all those road users whose plan trajectories conflict with this interim trajectory is necessary. For this purpose, the interim trajectory I-NK can be sent to other road users in the form of a desired trajectory as an MCM message. In order to prevent sending cooperation wishes too often and thus inefficient cooperation behavior, the cooperative maneuver planner contains the MinCR (***Minimal** Cost Reduction*) parameter, which specifies a minimum cost reduction for sending a wish. Thus, an intelligent vehicle always sends a wish if the cost of the interim trajectory I-NK is less than the cost of the interim trajectory I-AK by at least the amount of the MinCR parameter. In the exemplary situation shown in Figure 10, it is assumed that there is a corresponding cost saving, so that V01 uses the interim trajectory I-NK to send a wish trajectory (W-V01) as MCM message in this planning cycle ($t_{2.2}$). V01 uses the collision-free interim trajectory I-AK as the plan trajectory (P-V01) in this planning cycle.

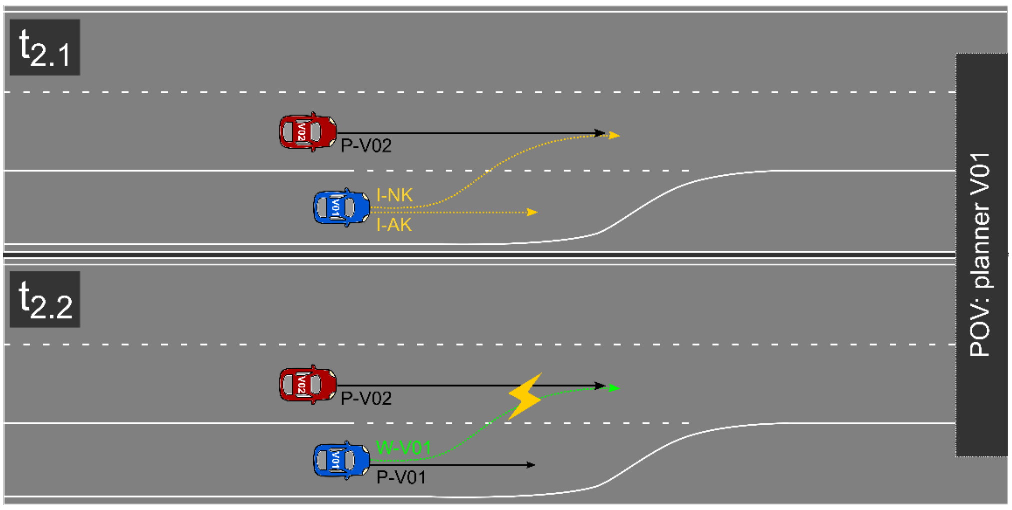

Figure 10: Illustration of a planning cycle at the threading lane as seen by V01.

As soon as the planner instance of a cooperative partner receives a request of a cooperative vehicle in the form of an MCM message, it has to consider whether the request should be accepted. Figure 11 shows such a situation from the point of view of the planner of V02. Since the interim trajectory I-AK must be collision-free with the wish trajectory of V01 (W-V01), this represents a lane change to the left lane of the highway. In this case, a more favorable interim trajectory I-PK results, which ignores collisions with the desired trajectories of other road users and thus does not make a lane change. In such a situation, the question for the cooperator (in this case V02) is to find a tolerable level of additional cost that is accepted in order to accept the incoming request. For this purpose, V02 compares the costs of the two interim trajectories I-AK and I-PK. In order to prevent too frequent acceptance of cooperation requests and thus inefficient cooperative behavior considered in the overall system, the cooperative maneuver planner contains the parameter MaxCI, which specifies the *maximum cost increase.* In this context, a road user always accepts a request if the cost of the interim trajectory I-AK exceeds the cost of the interim trajectory I-PK by a maximum amount equal to the parameter MaxCI. Accordingly, two results for the planning cycle are shown in Figure 11 ($t_{3.2}$). In case of a positive decision, V02 uses I-AK as the new plan trajectory ($t3_{.2\_accept}$). On the other hand, if the cost increment exceeds the value of MaxCI, V02 uses I-PK as the new plan trajectory ($t3_{.2\_denial}$), so that V01's desired trajectory continues to conflict with V02's plan trajectory. In this case, for reasons of traceability of the planner behavior, the I-AK is visualized as a so-called "evaluation trajectory" in simulation environments. However, this trajectory does not influence the cooperation behavior and, in contrast to plan and desire trajectories, is not sent as an MCM message.

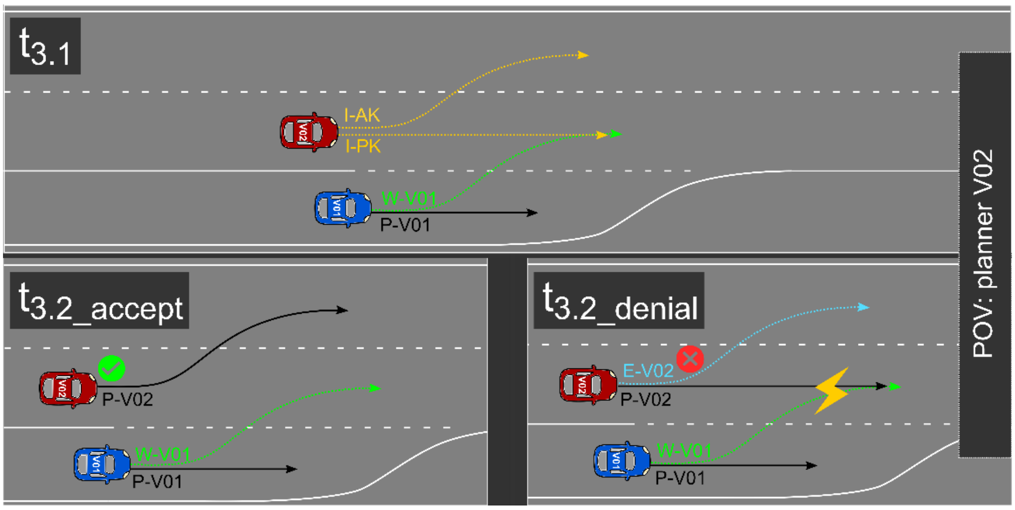

Figure 11: Illustration of a planning cycle with incoming desire trajectory of V01 as seen by the planner of V02.

Figure 12 represents the planner's view of V01 in one of the subsequent planning cycles. In the case of accepted cooperation in t_3 , V-02's plan trajectory (P-V02) no longer conflicts with the requested lane change, so the interim trajectory I-AK represents a threading operation ($t4_{.1\_accept}$). Thus, I-AK can be used by V01 as a plan trajectory ($t4_{.2\_accept}$). In case of a rejection of cooperation in the planning cycle t_3 , the I-AK also represents a slowdown in the threading lane in the planning cycle t_4 ($t4_{.1\_denial}$). Analogous to the time t_3 , a more favorable interim trajectory I-NK would be stored, which ignores the collision with the plan trajectory P-V02 . If also in this planning cycle the cost of I-NK falls below the cost of I-AK by at least the factor MinCR, V01 again sends a desired trajectory W-V01 as MCM message. The interim trajectory I-AK is used as the plan trajectory, so V01 would decelerate on the threading lane ($t4_{.2\_denial}$). In a subsequent planning cycle, V02 would again consider the incoming desired trajectory W-V01 when selecting its plan trajectory according to the procedure described. This continuous, iterative sending and evaluation of plan trajectories allows both planner instances to react to changing conditions at any time. Finally, Figure 13 shows a possible outcome of the threading process in case of cooperation (t5_accept) or continuous rejection (t5_denial) of V02's cooperation requests.

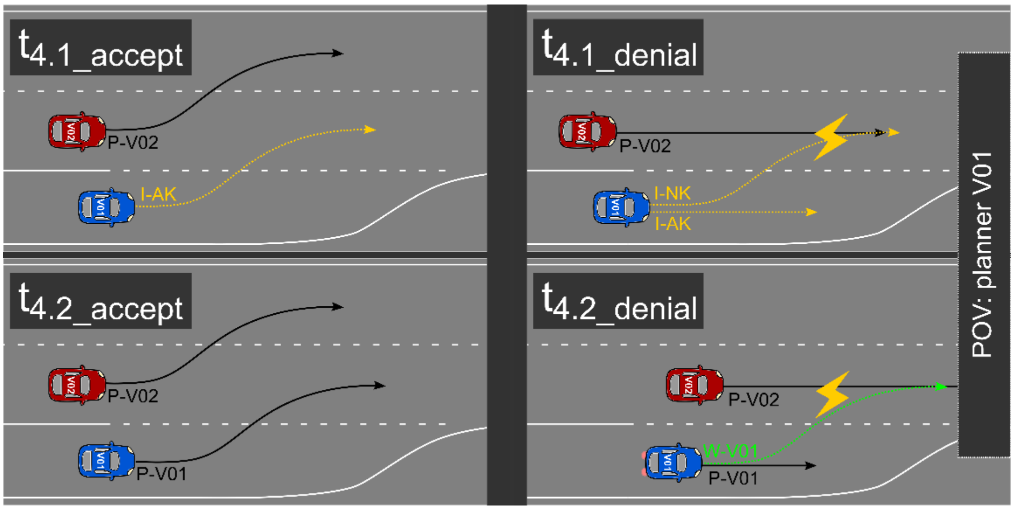

Figure 12: Representation of a planning cycle from V01's point of view, depending on whether V02 accepted (left) or rejected (right) V01's cooperation request in planning cycle t3.

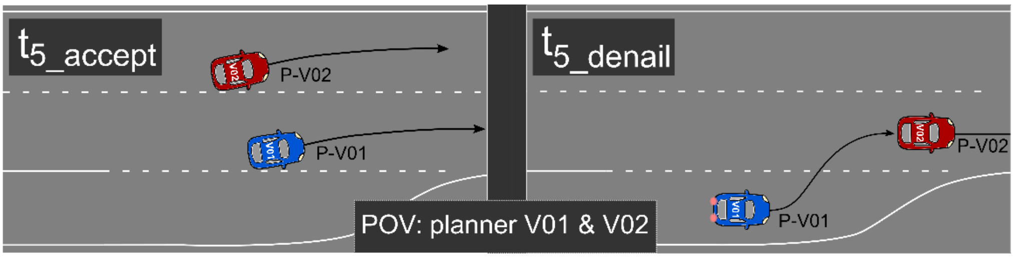

Figure 13: Plot of the plan trajectory of V01 and V02 at a later time, depending on whether V02 accepts a cooperation request from V01 during the threading process (left) or continuously rejects all incoming request trajectories (right).

3.4 Concept presentation OPEL

In the course of the IMAGinE project, several partner-specific solutions for cooperative maneuver planning and coordination have been developed at OPEL, which are described in this chapter. These mainly include the *Opel Core* [1] procedure as well as the procedures of cooperation by alternative trajectories and cooperation by objectives.

3.4.1 OpelCore 2018/19

The OpelCore 2018/19 procedure (hereinafter referred to as *Opel Core*) is an implicit, continuous, decentralized, intention-based coordination procedure. This means that participating vehicles can directly exchange their intentions in the form of trajectories via ad-hoc or cellular V2X communication in order to cooperatively plan and coordinate maneuvers. This procedure was developed at OPEL in a prototypical form and used for simulative investigations of the influence of cooperation on traffic quality.

A vehicle equipped with *Opel Core* technology requires a permanent transmission of only one trajectory in order to save the amount of data exchanged via V2X communication and thus reduce the channel load. Moreover, this characteristic makes the procedure suitable for use in mixed traffic (i.e., between autonomous and manually controlled vehicles), since cooperation in this case takes place on the basis of only one trajectory per participant. In the case of manual driving, the trajectory is derived from the observation of vehicle movement and driver behavior. Cooperative maneuvers with *Opel Core* include deceleration, acceleration, and lane changes, as well as support cascaded (i.e., multiple sequential) coordination processes. Comparable to the IMAGinE 2018 approach, a trajectory in *Opel Core* can belong to one of three different types depending on the intentions it symbolizes. These trajectory types are:

- Reference - default, if no cooperation active
- Request - Request cooperation (without right of way)
- Offer - Offer cooperation (with right of way)

If a non-communicating vehicle, which accordingly cannot transmit trajectories, is present in a cooperative situation, a Most Probable Trajectory (MPT) must be estimated (e.g., based on vehicle dynamics) and used as a substitute for its Reference Trajectory. The principle of cooperative maneuver matching with *Opel Core* Algorithm is shown in the following illustration of an exemplary scenario of cooperative merging at interchanges (function F1).

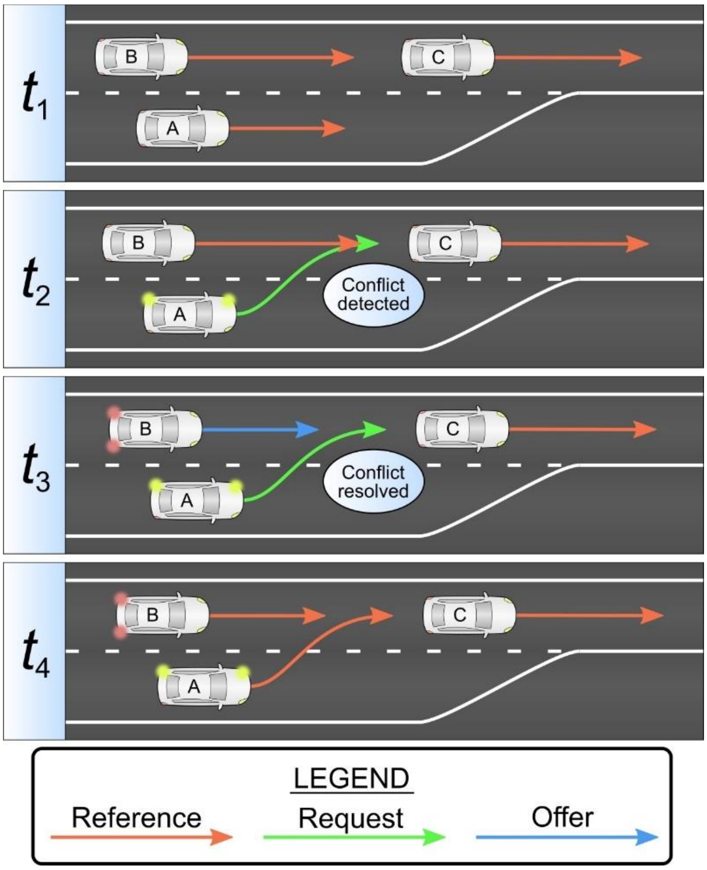

Figure 14: Concept of cooperative maneuver coordination - OpelCore 2018/19 [1].

As can be seen here, at time t_1 all vehicles initially follow their original reference trajectories without conflicts. At time t_2, as soon as vehicle A intends to change lanes, it sends a request trajectory that causes a conflict with vehicle B's reference trajectory. In this case, vehicle B may give up its right-of-way and cooperate by decelerating to increase the gap to vehicle C necessary for vehicle A to change lanes. At time t_3, after vehicle B cooperatively adjusts its trajectory and sends it as an offer trajectory, the conflict is resolved. At time t_4, vehicle A can follow its new Reference trajectory and merge.

Opel Core algorithm is executed independently in each vehicle actively participating in the co-operation. This results in a continuous and decentralized process of negotiation and decision making, so that each vehicle can autonomously, simultaneously cooperative or non-cooperative, determine its course of action based on its own maneuver planner and the information from V2X communication.

3.4.2 Other procedures

3.4.2.1 AltTraj 2018 - Cooperation through alternative trajectories

In this method, each vehicle plans an ideal and a so-called hesitation trajectory, which are exchanged via V2X communication. The hesitation trajectory follows the same path as the ideal trajectory, but has a slower speed profile and is therefore spatially shorter with the same planning horizon. Normally, the ideal trajectory is followed. In a cooperative traffic situation, if ideal trajectories of several vehicles cause a conflict, a numerical-combinatorial set of rules is used to find the solution (global) where the majority of vehicles can follow their ideal trajectories. Thus, the minority of vehicles travel their hesitation trajectories, resolving the conflict cooperatively. The concept of cooperation through alternative trajectories is demonstrated using an intersection in the figure below.

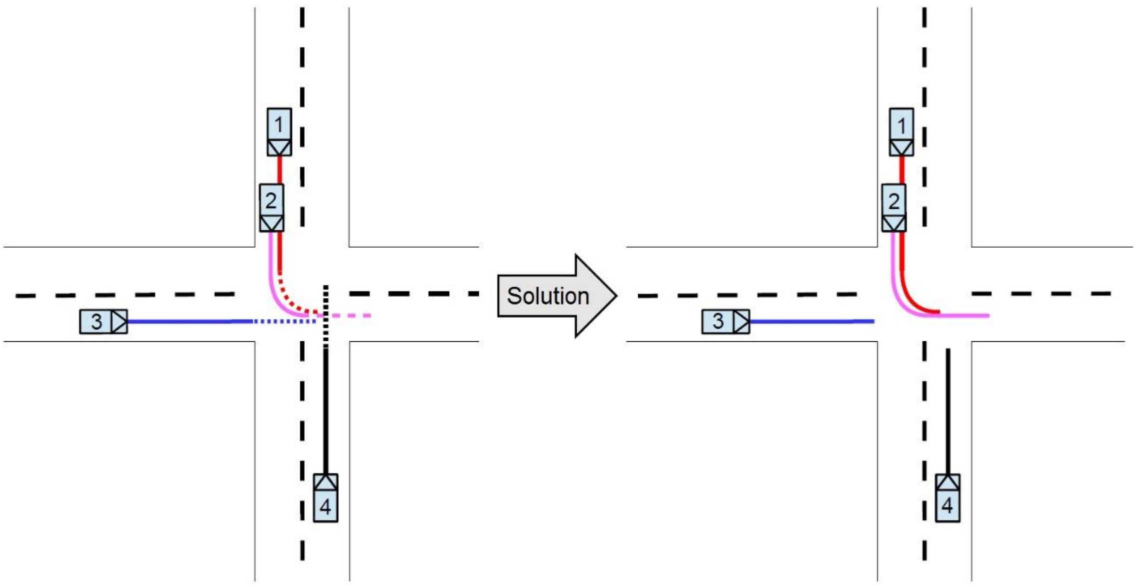

Figure 15: Concept of cooperative maneuver coordination - AltTraj 2018.

As shown here, initially the ideal trajectories of vehicles 1, 2, 3 and 4 all collide at the intersection. A solution to this conflict is achieved by having vehicles 1 and 2 follow their ideal trajectories (longer lines) and vehicles 3 and 4 follow their hesitation trajectories (shorter lines).

3.4.2.2 Targets 2019 - Cooperation through targets

In this method, each vehicle plans one long-term destination (a location), several medium-term destinations (roads), and several short-term destinations (positions), all of which are exchanged via V2X communication. In this process, the medium-term destinations are first generated from the long-term destination, and the short-term destinations are generated from the corresponding medium-term destinations internally in the vehicle based on its planned route. As soon as its own vehicle receives destinations from other vehicles, it models their future movement in the form of trajectories, for example, although this modeling becomes increasingly imprecise with increasing distance. If a conflict is detected in the process, the vehicles search for a cooperative solution. For this purpose, an overall cost function is evaluated in each vehicle, which is used to find an optimum (global). The concept of cooperation by objectives is demonstrated by means of a single and a multiple bifurcation in the following figure.

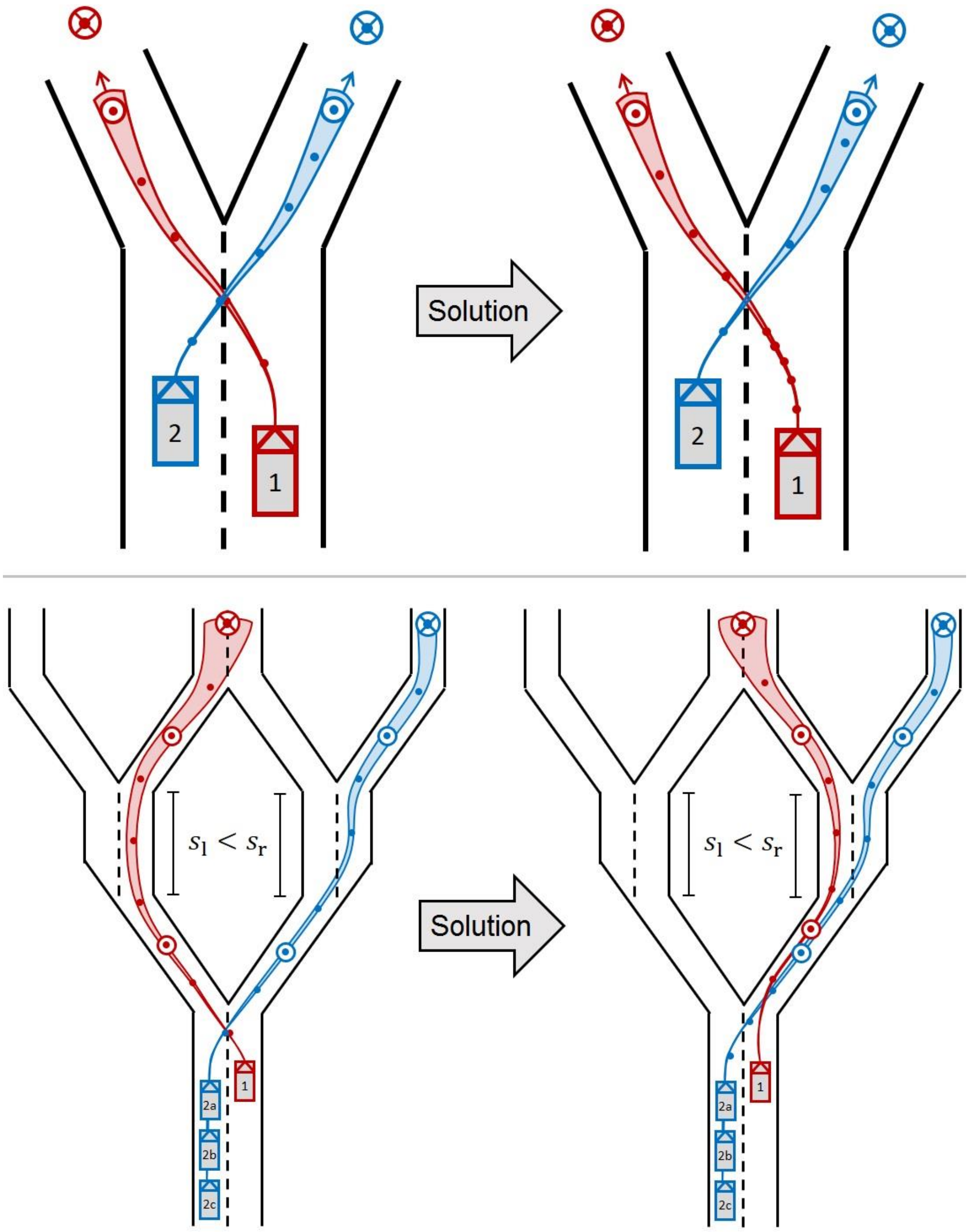

Figure 16: Concept of cooperative maneuver coordination - Targets 2019

This figure depicts cooperation based on long-term (large circles), medium-term (medium circles), and short-term (small circles) goals. As shown in the upper part, vehicles 1 and 2 have a conflict that is resolved by adjusting the short-term goals by having vehicle 1 pass the fork slower and vehicle 2 pass the fork faster. As shown in the lower part, vehicles 1 and 2a, 2b, and 2c have a conflict that is resolved by adjusting the medium-term and short-term goals by having vehicle 1 reschedule its route to the (slightly longer) right road so as not to impede the column of vehicles 2a, 2b, and 2c.

3.4.2.2.1 Sources

[1] V. Lizenberg, D. Bischoff, Y. Haridy, U. Eberle, S. Knapp & F. Köster. "Simulation-Based Evaluation of Cooperative Maneuver Coordination and its Impact on Traffic Quality." *SAE International Journal of Advances and Current Practices in Mobility*; vol. 3, no. 6, pp. 3159-3169; Technical Paper 2021-01-0171. 2021; doi: 10.4271/2021-01-0171.

3.5 Concept presentation BMW

3.5.1 Maneuver coordination concept "Bbasic

The concept was developed in IMAGinE by BMW.

In the "Bbasic" concept, no motion areas / trajectories are used. This reduces the bandwidth requirement for communication to a fraction of the bandwidth required for the transmission of one or more planned trajectories.

Furthermore, in this procedure, the MCM only needs to be exchanged in an event-oriented manner when a need for cooperation is seen. Communication thus requires minimal bandwidth overall.

The tuning is based on the tuning of human drivers and is suitable for mixed traffic with manually controlled vehicles, since it can do without the prediction of reference trajectories, which is difficult and uncertain in mixed traffic. Communication with manually or assisted controlled vehicles can still be done unambiguously with this method without reference trajectories.

Thus, in the embodiment described above, this is an explicit, event-oriented, decentralized, intention-based coordination procedure. Cooperation-relevant intentions are communicated by directly and unambiguously communicating a need for a target lane. Optionally, the desired cooperation partners are also directly named. Further variants are described below.

The procedure enables targeted addressing of messages to exactly the road user(s) who are asked for cooperation or who are informed of their own willingness to cooperate. For example, for IMAGinE function F1, a single, all, or all rear vehicles can be selectively addressed and asked for cooperation.

The procedure can also be used as an interoperable fallback level for other maneuver coordination concepts. The proposal put forward for discussion is also that vehicles are not mandatorily obliged to exchange MCMs, even if this appears socially desirable as a rule given the technical possibility in the vehicle.

3.5.2 Maneuver coordination concept "BBB

The concept uses two-dimensional movement areas beyond trajectories. It can also be activated and deactivated event-driven, but it can also be permanently activated (see "Bbasic").

3.6 Concept presentation Mercedes-Benz AG/DCAITI

The maneuver coordination concept of Mercedes-Benz and the DCAITI envisages realizing cooperative driving functions by negotiating roles. The reasons for this are, for example, longer-term, i.e. tactical and strategic, maneuver coordination, which is difficult to realize with a trajectory approach due to V2X channel load capacities. These functions can be, for example, driving in a platoon (cooperative longitudinal guidance) or overtaking trucks on the highway. Furthermore, the role-based concept can be transferred to other cooperative functions, such as threading at interchanges. The basic idea of this concept is based on distributed, synchronous state machines. The following figure shows an example of the state machine for the function F2 - Platooning.

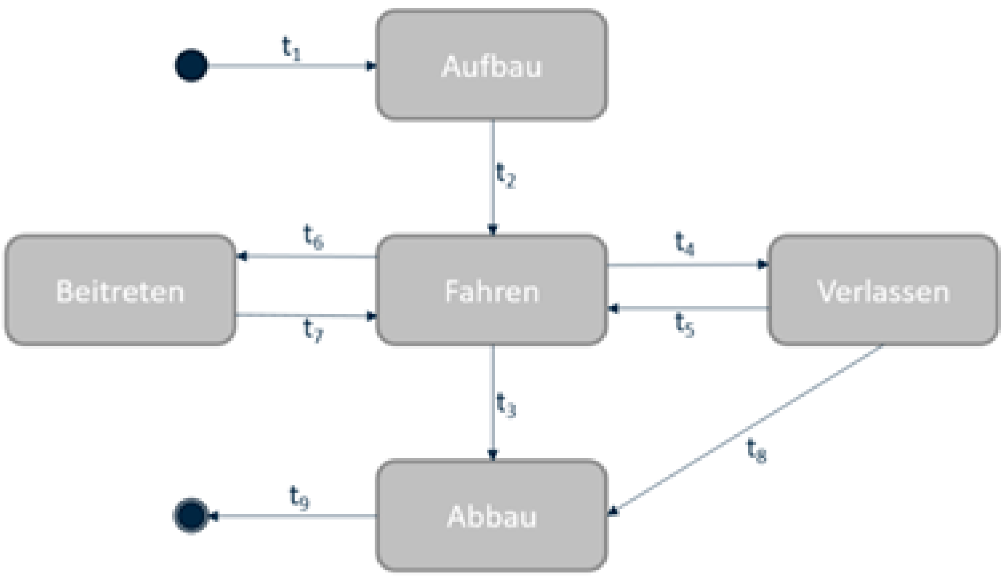

Figure 17: State machine function F2

This concept provides for explicit maneuver execution - maneuver coordination is performed by the negotiated role. Each vehicle then executes the maneuver based on the implementation of that role. The coordination is done through the Collaborative Maneuver Protocol (CMP).[1]

The following figure shows the role-based concept in the "Join" platoon state. Vehicle 3 intends to join the platoon. A cooperation request from vehicle 3 initiates a coordination process. If the

1 Sawade, Oliver, Matthias Schulze, and Ilja Radusch. "Robust communication for cooperative driving maneuvers." *IEEE Intelligent Transportation Systems Magazine* 10.3 (2018): 159-169.

other vehicles agree to the request, the vehicles switch to the "Join" platoon state. Vehicle 2 infers from this State-Machine-State by its role that it should open a gap for vehicle 3. Thus, vehicle 2 adjusts its trajectory as shown. After vehicle 3 has joined the platoon, all participants will switch back to the "driving" state.

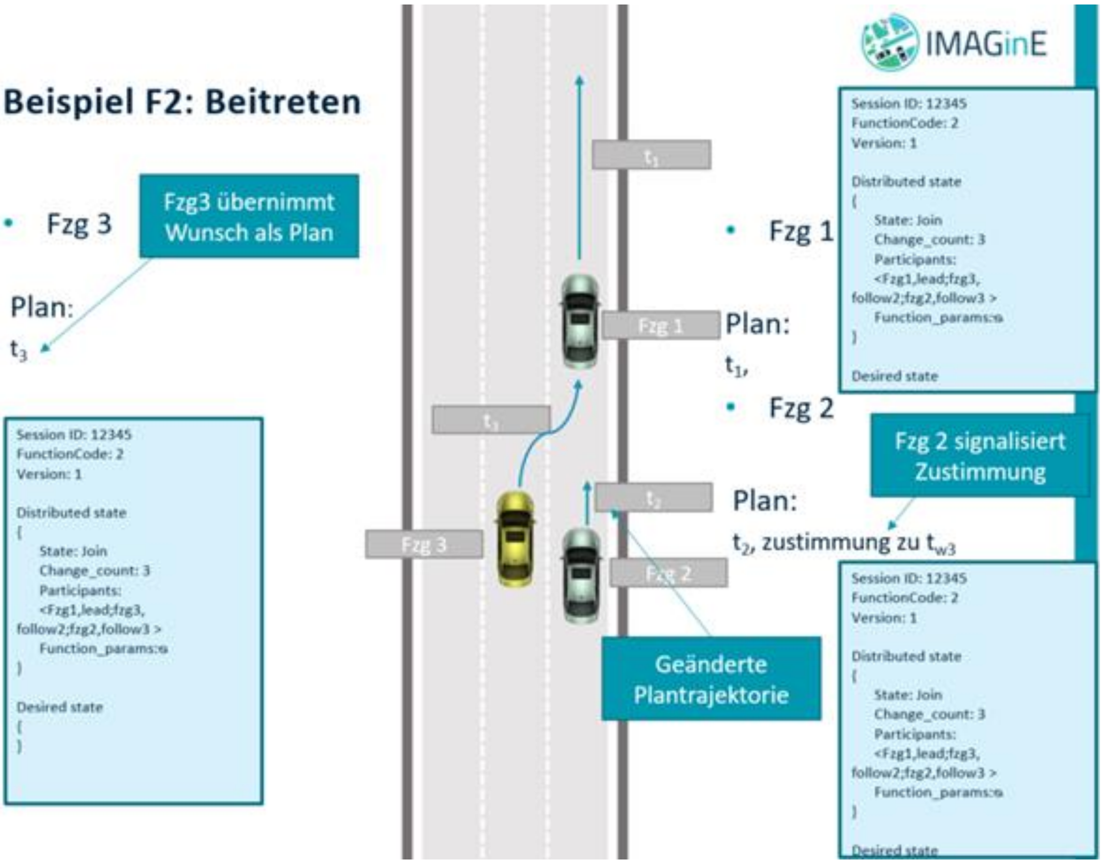

Figure 18: Role-based concept in the "Join" platoon state

The change from one state to another is done by a voting mechanism. The vehicle that wants to trigger the state change sends a request message. The other vehicles can agree, disagree or respond with another proposal to this change. All messages are time-stamped, have a one-to-one ID and a list of participants in the cooperation session. Only when all vehicles have agreed, a switch is moved to the next state. Control messages guarantee that all vehicles are always in the same state of the distributed state machine.

3.7 Concept presentation MAN - Cooperative longitudinal guidance (F2)

In the following, the concept is described, which is based on the dissertation of Jürgen Hauenstein. The basic idea has already been published in [1]. In addition, a publication with the concept was submitted to the MDPI Journal Electronics.

3.7.1 Motivation

Fuel costs are one of the largest cost components in the total cost of ownership for long-distance haulage companies [2, 3], which is why, in addition to maneuver coordination, cooperative longitudinal guidance must also map energy-efficient driving. For this purpose, the representation of coasting processes in particular is a decisive factor, as it is already used in GPS-supported cruise control systems, e.g. Efficient Cruise at MAN [4], in series production. Due to the high mass of heavy commercial vehicles, coasting processes can extend over several kilometers, which usually exceeds the planning horizon of maneuver coordination, e.g., threading on highways (function 1), which is why an additional level in the form of a strategic trajectory is necessary in the concept.

3.7.2 Concept

3.7.2.1 Concept overview

Maneuver coordination with other road users is performed with the concept of exchanging planned and desired trajectory via V2X [5]. The plan trajectory is always sent and represents the current schedule according to the road rules. The plan trajectories are collision free with other plan trajectories. The desired trajectory is sent out when a desired trajectory cannot be driven according to the road rules, it is in collision with at least one plant trajectory from another road user. One of the advantages of this method is the relatively low resource consumption for the communication channel with a maximum of two trajectories. In addition, this is a generic procedure, which is why no situation analysis is necessary. In contrast to the IMAGinE 2018 cooperation concept (D2.5), trajectories are not exchanged in Freenet format but in UTM format.

Trajectory format (google protobuf message definition of Maneuver Coordination Messge MCM):

```
syntax = "proto3";

message MCM {
  uint32 v2xId = 1; // V2X station ID
  int64 timestamp = 2; // time in us
  Trajectory planTra = 3; // planed trajectory
  optional Trajectory desireTra = 4; // desired trajectory

  message Trajectory {
    repeated PolySection longPos = 1; // UTM-easting
    repeated PolySection latPos = 2; // UTM-northing

    message PolySection {
      repeated float coefficients = 1; // coefficients of polynomial a_0,
a_1, ...
      float start = 2; // start time in s, first section start always with
zero, real time = timestamp + start
      float end = 3; // end time in s
      float xOffset = 4; // UTM offset, whole number (accuracy float32 8-9
numbers)
    }
  }
}
```

Calculation of positions:

x(t)=$a_0 + xOffset + a_1 * t + a_2 * t^2 + a_3 * t^3$+?
Mit t=[start, end] und x der entsprechenden UTM-Koordinate.

Note on the defined trajectory format:

The float32 values must be converted to float64, otherwise the accuracy in UTM is not sufficient.

Further, it is assumed that the vehicles move in the same UTM zone, otherwise an additional field for the UTM zone would have to be introduced in the message definition and, if necessary, trajectories would have to be converted from one zone to the other.

Another limitation is that UTM does not cover the poles of the world, for example, but it does cover the roads of the world to the greatest extent possible.

The defined format tries to use as little memory as possible to keep the channel load low. For this reason, for example, the heading must be calculated from the trajectory with the assumption that the vehicle is oriented along the trajectory. For stationary objects, the heading must either be taken from the Cooperative Awareness Message (CAM) [6] or from the board sensor's own measurement, or estimated with additional assumptions, such as vehicle is oriented along lane. In addition, the trajectory does not contain altitude data. The height can be crucial for collision detection of trajectories at e.g. underpasses or bridges. Here again, the data from the CAM or *the on-board sensor system and possibly a road model must be used to decide whether vehicles are on the same road or lane.*

The planning horizon due to the limited computing capacity is relatively small, e.g. 10 seconds. For a journey at 80 km/h, the planning horizon is thus approx. 222 m, which is too short for energy-efficient driving.

The strategic trajectory represents the optimal driving strategy with a long horizon, e.g. 3 km, without considering other road users on lane center. It is an additional component. It is used to realize long rolling maneuvers that go beyond the horizon of the planned and desired trajectory. As a rule, the strategic trajectory is driven when there is no cooperation with other road users, thus the behavior of GPS cruise control is represented.

3.7.2.2 Detailed description

The following figure shows a simplified overview of individual components.

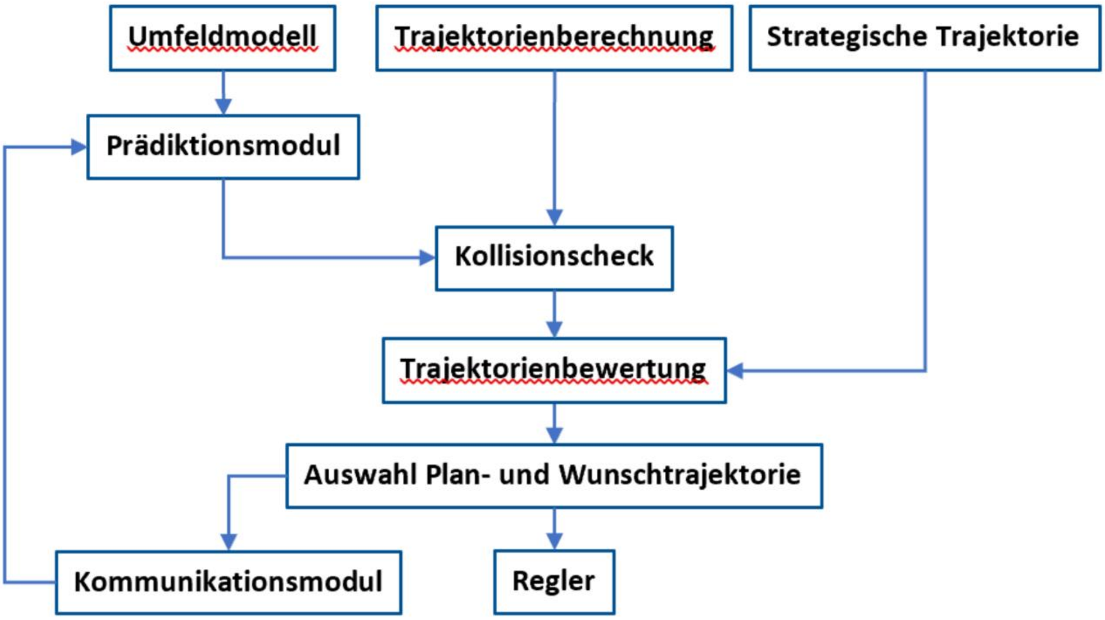

Figure 19: Simplified component overview of the cooperative longitudinal guidance system for commercial vehicles

In the first step, a strategic trajectory is calculated. There are various concepts in the literature on how GPS cruise control can be implemented, e.g. [7-11]. This is also called eco-driving or look-ahead control. The important thing here is that a trajectory is continuously output. A heuristic method was chosen for the implementation, among other things because of the low computing capacity required.

In addition, a trajectory set is calculated for the selection of trajectories for cooperative maneuver coordination. The trajectories should include energy-efficient trajectories with rolling maneuvers and should be physically drivable. For longitudinal guidance, driving along a given path or lane center can be assumed. There are a variety of methods for computing trajectories, for example, an overview is given in [12]. Among other things, because of the physical driveability, a graph-based trajectory calculation was used in the implementation.

The trajectories are then compared for collision with other trajectories from other road users. The objects are provided by an environment model. Trajectories of non-V2X vehicles are estimated. These are assumed to be moving along the lane. Trajectories of V2X vehicles are taken from the MCM and assigned to the corresponding objects.

The collision check verifies that the safety distance is maintained in accordance with the German Road Traffic Act (StVO). Due to inaccuracies, e.g. in the measurement data acquisition or determination of the position or the trajectory traversal, a multi-stage collision check is performed. The trajectories are assigned tolerances. If these are exceeded when the trajectory is traversed, a reset to the current position is performed, otherwise trajectories are always calculated further from the planned point of the last plant trajectory at the given time. This means that the actual distance can deviate by a factor of two from the tolerance for trajectories, and in the case of unfavorable resets this changes abruptly. In addition, numerical inaccuracies in the calculation from one calculation cycle to another can result in a changed distance dimension, i.e., with a safety distance of, for example, 50 m, the calculated distance changes from, for example, 50.000 000 000 1 m to 49.999 999 999 8 m. If this is the initial distance, no calculation of collision-free trajectories are possible in this example. For these reasons, there are three collision checks with different distances:

- Stage 1: Safety distance according to StVO + tolerances of the trajectories
- Stage 2: Safety distance according to StVO in first e.g. 3 seconds, otherwise like stage 1.
- Level 3: Safety distance according to StVO

As a rule, only trajectories corresponding to level 1 are selected. In the event that no collision-free trajectories are found in all three stages, an emergency maneuver in the form of braking is initiated.

Subsequently, an evaluation of the trajectories is performed. By comparing the speed profiles of the strategic and the calculated short trajectories for V2X, reasonable rolling operations with a long planning horizon can be identified and executed. This represents a cost function. This also ensures that vehicles move at an appropriate speed when the road is free. In addition, energy efficiency and fulfillment of desires are included in the cost calculation. The drivable trajectory with the lowest cost is set as the plant trajectory. If another trajectory is significantly less expensive, then this is also set as the wish trajectory. Furthermore, accepted wishes are stored and treated as a planned trajectory in the next step, even if this vehicle or these vehicles do not have the right of way according to the StVO.

In the last step, the trajectories are sent via the communication module and the plant trajectory is transferred to the controller so that it can be traversed. For transmission with V2X, depending on the calculation method of the trajectories, these must be converted into polynomials.

The entire calculation of the calculation steps is cyclic and is not event-based.

3.7.3 Sources

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3.8 Concept presentation MAN - Cooperative truck overtaking maneuvers

In the following, the concept is described, which is based on the dissertation of Jan Cedric Mertens.

3.8.1 Motivation

Truck overtaking maneuvers on the highway are often considered an obstacle by car drivers. However, this does not mean the many fast truck overtaking maneuvers that go unnoticed thanks to attentive truck drivers, but the so-called "elephant races". In this case, a truck overtakes another truck at such a low differential speed that the overtaking time is more than 45 s and thus, according to the Higher Regional Court of Hamm, an inadmissible obstruction of the traffic behind occurs.

However, truck overtaking maneuvers in themselves are part of a healthy traffic flow, as they prevent excessive clustering in the right lane and equalize the speed difference between the lanes. A general ban on truck overtaking would therefore be detrimental to traffic flow.

So if truck overtaking maneuvers cannot be banned, consideration should be given to how they can be optimized through cooperation. The primary goal is to increase safety and efficiency, but in addition the truck driver should be relieved and cooperation between future automated vehicles should be worked towards.

Figure 20: Elephant race blocs the fast lane

3.8.2 Initial situation

The initial situation for the truck overtaking maneuver is shown in the figure below. A fast truck1 is behind a slower moving truck2, while passenger cars are rapidly approaching from behind. In this situation, a decision has to be made whether and how to perform an overtaking maneuver by weighing the potential costs for all parties involved.

Figure 21: Initial situation for the truck overtaking maneuver. (Graphic created with C2C-CC Illustration Toolkit © Car2Car Communication Consortium).

3.8.3 Optimization approach

There are three approaches to the cooperative truck overtaking maneuver:

- Reduced safety distance: Reducing the safety distance from 50 m to a platooning distance reduces the relative passing distance and thus the passing time. While this approach is also frequently used by truck drivers in practice, without V2X it is extremely dangerous and can lead to rear-end collisions. So during the reduced safety distance, braking signals must be transmitted from the front truck to the rear truck.

- Selection of the overtaking point: Due to the dynamic GPS cruise control, trucks usually do not drive at a constant speed, but continuously adapt it to the topology. For example, the truck can roll over the crest of a hill at a lower speed in order to accelerate again on the downhill slope. The choice of speed depends heavily on the driver's settings, but also on the load and the engine. Thus, since the speed profiles of the trucks are dynamic, the differential speed of the trucks can also vary over the coming distance. By superimposing the planned speed profiles over the coming kilometers, it is therefore possible to identify sections where the differential speed is particularly high.
- Adjusting the speed: To further increase the differential speed, the speeds of the trucks can also be actively adjusted during the overtaking maneuver, within a cooperation margin. This leads to a reduced overtaking time and thus to less obstruction for passenger car traffic.

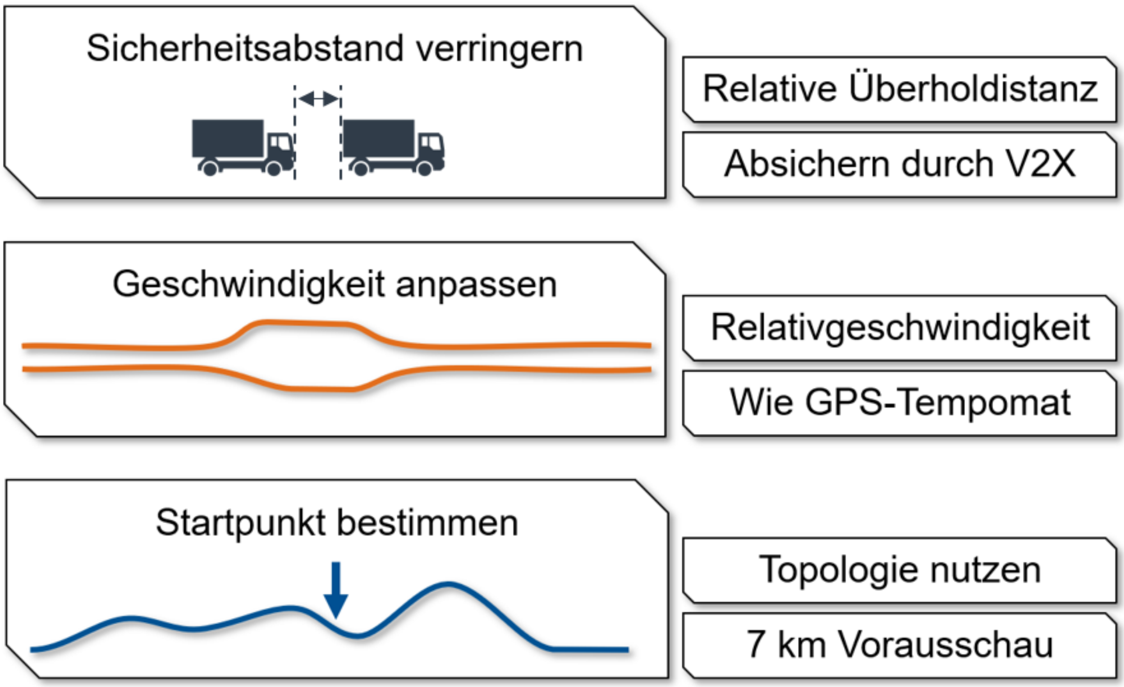


Figure 22: Three approaches for optimizing cooperative truck overtaking maneuvers.

3.8.4 Maneuver Planning

Maneuver planning for the cooperative truck overtaking maneuver takes place on a strategic level, generating no trajectories but recommended actions for the truck driver via an HMI.

Based on the speed profiles of the GPS cruise control systems, the location where the fast truck catches up with the slow truck is identified first. This is the first possible overtaking point. From there on, overtaking maneuvers are generated for the coming maximum 7 km in 10-meter sections as follows and stored in a list:

- Determine how much the fast truck must reduce its speed in order to catch up with the slow truck only at later overtaking points

- Based on the speeds of both trucks at the overtaking point, determine the required safety distance: Reaction_way_fastTruck + Braking_way_fastTruck - Braking_way_slowTruck
- Initiate the lane change when the reduced safety distance is reached
- The fast truck fully exploits its cooperation potential by accelerating.
- The slow truck fully exploits its cooperation potential by coasting.
- Based on the speeds of both trucks, the necessary safety distance for rejoining is determined (analogous to 2).
- When the reduced safety distance is reached, initiate the lane change back.
- The fast truck rolls out to its original desired speed.
- The slow truck accelerates to its original desired speed.

Then, the created list of overtaking maneuvers is gone through and the individual overtaking maneuvers are monetarily evaluated based on the required fuel and time of the involved trucks and cars. The overtaking maneuver with the lowest cost is used for maneuver reconciliation in the following.

3.8.5 Maneuver reconciliation

The maneuver coordination is based on Oliver Sawade's concept with distributed state machines (see also concept presentation Mercedes-Benz AG/DCAITI). The cooperative truck overtaking maneuver is divided into several states for this purpose. In each state there are atomic maneuver plans for the fast truck and the slow truck, such as "accelerate to your full cooperative potential". These states form a distributed state machine with conditions for state transitions such as "When the reduced safety distance is reached, change to the state 'lane change to the left'".

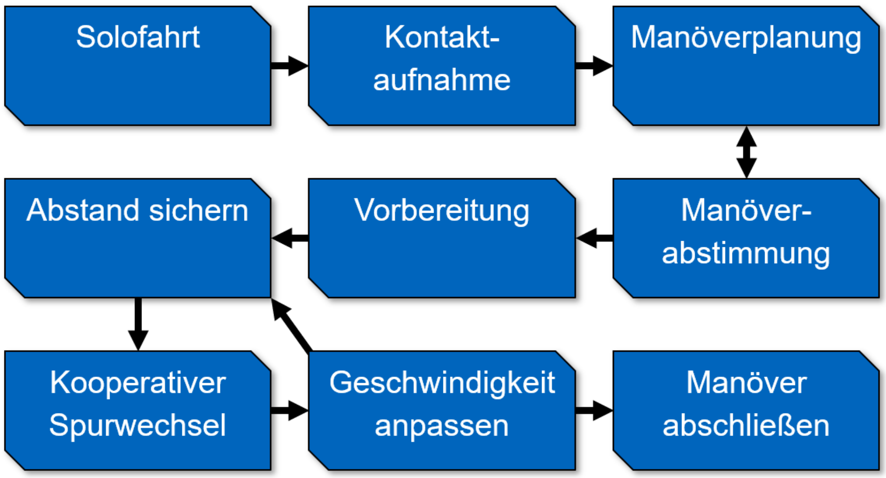


Figure 23: Distributed state machine for the cooperative truck overtaking maneuver.

A key feature of this concept is also that state transitions can only be performed synchronously between trucks, for which a new message, the IDSM, has been introduced. The structure of the

IMAGinE Driving Strategy Message (IDSM) is generic so that it can be used generally for strategic coordination across distributed state machines, and is shown in the figure. The first element is the header followed by the actual driving strategy content. "Nature" can be used to specify which function-specific maneuver planning is currently active and which distributed state machine should be used. This is followed by a required "Current Session" and an optional "Desired Session". Both contain a "State ID" to convey which state of the distributed state machine the vehicle is currently in, or which state it would like to change to. In each case, this includes a "Payload" that contains the entire parameterization of the distributed state machine. In the case of the "Desired Session", a "Vote Timeout" is also included, which specifies how long the desire is valid. Another part of the session is a list of current or desired participants, in the form of a unique participant ID and role assignment. In order to exchange additional participant-specific information that is not already covered by the CAM or DENM, a "participant payload" can be sent along. Since this payload applies to both sessions, it is only sent in the "Current Session". With the "Current State" the participating vehicles send continuously in which state they are at the moment. If the condition for a state change is fulfilled in this state, the vehicle also sends the "Desired State" via the IDSM. Only when all the vehicles involved send the identical "Desired State" is the state change performed synchronously.

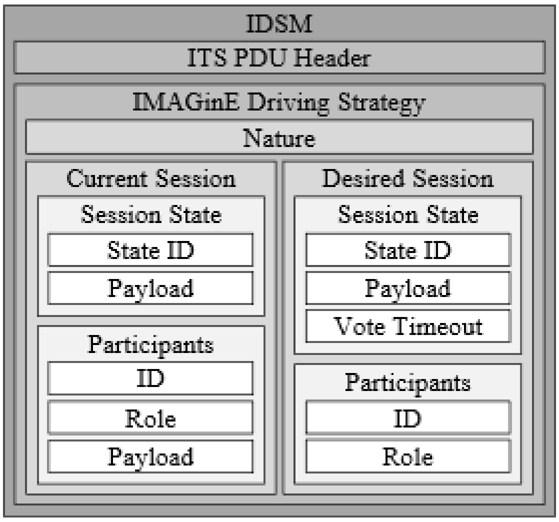


Figure 24: Description of the generic part of the IDSM

In addition to the generic part of the IDSM, further contents have to be defined specifically for the cooperative truck overtaking maneuver: The "Session Payload" and the "Participant Payload", as shown in Figure 25 Within the IDSM, these are defined as optional byte arrays and only by referencing the cooperative function from the "Nature" attribute can the appropriate deserialization be selected. All parameters necessary for maneuver planning are mapped in the "Participant Payload". The planned maneuver can then be uniquely described at the strategic level by the six elements of the "Session Payload". If the "Session Payload", which was determined independently by the two trucks, matches except for small deviations, it can be assumed that both trucks want to perform the identical maneuver. The elements of the "Session Payload" are then used to parameterize the distributed state machine.

Session Payload	Participant Payload
Cooperation Mode	Cooperation Mode
Start Position	Set Velocity
End Position	Min Hysteresis
Duration	Max Hysteresis
Safety Gap Pre	Weight
Safety Gap Post	Engine

Figure 25: Description of the function-specific part of the IDSM

3.9 Concept presentation Autobahn GmbH

In the following, the concept of cooperative-strategic traffic distribution (F4) of Autobahn GmbH is presented.

3.9.1 Motivation

Until now, navigation and route recommendations have been determined only on the basis of travel time losses and route lengths, regardless of the medium, such as in-vehicle navigation systems or infrastructure-based dynamic wayfinding systems. Moreover, an integration of locally collective strategic route recommendations is independent of individual navigation, so that they contradict each other in the worst case. Thus, an optimized traffic distribution in the available road network taking into account the available capacities is also not possible so far.

The goal of the "Cooperative-strategic traffic distribution" function is to optimize traffic distribution by taking into account collective strategies and individual cooperative coordination based on and using additional criteria for route selection.

3.9.2 Concept

Figure 26: Situation in function F4: decision point. (Graphic created with C2C-CC Illustration Toolkit © Car2Car Communication Consortium).

Maneuver planning for cooperative-strategic traffic distribution takes place at a strategic level and does not generate trajectories, but rather recommended actions for drivers via an HMI. As part of the "cooperative-strategic traffic distribution" function, vehicles send information to a strategic support to determine parameters on main and alternative routes. This strategic support implemented on a server (also called support server or "SUPS" for short) can be covered, for example, by a cooperative traffic center. This determines an optimized distribution of traffic flows taking into account strategic routing based on the merged vehicle and infrastructure data and sends the distribution recommendation to the vehicle. The vehicles receive the data and reconcile it with their intentions regarding destination and route criteria before the corresponding decision points on their route. The strategic support then calculates the user- and collective-optimized routes. Such a decision point, where the choice is between a congested main route and an alternative route, can be seen in Figure 26. The concept of function F4 can be divided into six main steps:

Select and set route selection criteria

The selection and determination of route selection criteria is partly done manually and independently of the functional operation already before the start of the journey and partly by a determination of route criteria, which depend on driver behavior and vehicle status, during operation with on-board sensor technology.

In addition to the usual criteria for selecting a route, such as travel time or route length, further route criteria can also be included with regard to developments for automated driving. A distinction can be made here between route criteria that the driver selects manually and route criteria that are determined by the vehicle, taking into account driver behavior and vehicle status.

In addition to the classic route criteria of destination, travel time, route length and, if necessary, avoidance of toll routes, other driver-side route criteria are also possible. With regard to the possibility of pursuing other activities during automated driving, such as working, criteria such as smooth, quiet or fuel-efficient driving become important. Depending on the purpose of the trip, however, the desire for varied and beautiful surroundings or a driving route that is demanding in terms of the driving task can also be a criterion. The driver-side route criteria that can be selected at the beginning of the trip can be seen in Figure 27.

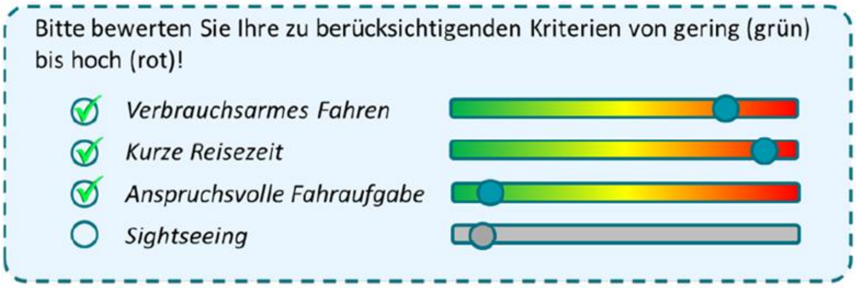


Figure 27: Driver-side route criteria

Due to the increasing intelligence and sensor technology in the vehicle, criteria that the vehicle determines are also relevant. The GPS position of the vehicle is compared with the stored map. In this way, it is detected on which lane the vehicle is located. If a change to the alternative route involves several lane changes, this increases the cost of selecting the alternative route. Furthermore, the vehicle type or purpose is important for a route selection. For example, not all possible routes can be used by heavy goods vehicles. In addition, in the case of a scheduled bus, the choice of route is limited as a result of the predefined stops, so that it is often only possible to use alternative routes to a very limited extent. Another criterion is the vehicle status, so that, for example, if the tank level is low, the route selection can be limited to routes that include a gas station.

Provide driving data (sensing)

In the second step, the vehicles transmit data to the strategic support, which are useful for generating a traffic situation. This includes the position, the direction of movement, and the speed of the vehicle. This data is first transmitted from the vehicles to an Intelligent Roadside Station (IRS) via WLAN according to the ETSI ITS G5 standard. Existing IRS can be used for this purpose; future distribution in the road network at strategically important points is planned as part of the digitization of the infrastructure. The IRSs send the data on to the SUPS via mobile communications. The driving data is transmitted as a Cooperative Awareness Message (CAM). Figure 3 shows the described message transmission between SUPS, IRS and the vehicles.

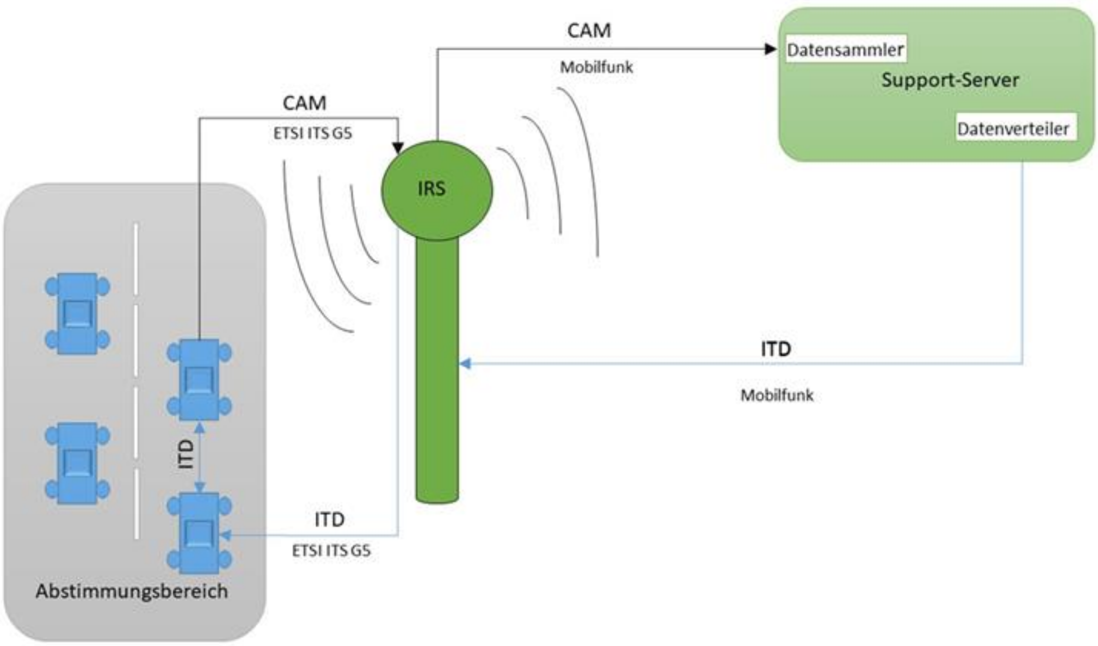


Figure 28: Message transmission between vehicles, IRS and SUPS

Determine traffic situation and strategies

Traffic situation determination and strategy determination are carried out on the SUPS. On the one hand, the data transmitted by the vehicles is used to determine the traffic situation; on the other hand, the available data, such as road works, traffic events or events, can be accessed via an interface to the Traffic Center Germany. The data from these two sources can be merged into a common model of the traffic situation, so that statements can be made about the loads and residual capacities on the routes.

The traffic situation is used to calculate an optimized distribution of traffic among the route options so that traffic disruptions are avoided and available capacity on highways and the base network is utilized. Here, priority is given to the utilization of capacity on the corresponding higher-level roads.

The traffic distribution is modified based on the equipment rate at the decision point, which has an important influence. The ratio between equipped and non-equipped vehicles is determined based on the infrastructure-detected traffic volume in relation to the number of vehicle-detected traffic volume.

Some validation of this concept will be done together with the overall traffic impact studies in work package WP5.3. This will be done by developing a macroscopic traffic model that includes careful traffic volume generation and network creation to represent as realistic a situation as possible on German highways. The more detailed description for this is given in deliverable D5.3.

As part of the research activities in the IMAGinE project, the "environment modeling" step will be scaled accordingly for implementation on the test site. On the test site, the tasks of the SUPS mainly consist of generating and sending the distribution recommendation (see section "Maneuver planning") and visualizing the positions and maneuvers of the vehicles.

Submit attributes for action guidelines and a distribution recommendation (maneuver planning).

The optimized distribution of traffic for a given decision point is called a "distribution recommendation". Assuming that capacity bottlenecks are present or approaching, the distribution recommendation is transmitted to the vehicles. The message type of the distribution recommendation is "IMAGinE Traffic Distribution" (ITD). As shown in Figure 28, this message is sent from the SUPS to the IRS via cellular and then to the vehicles via ETSI ITS G5. Within the ITD, two different types of information exist, called containers: the dispatch of the distribution recommendation is done via the so-called TrafficDistribution container, and the route selection reconciliation described in the next section is done via the Score container. Figure 29 shows the structure of the ITD and the contents of the two containers.

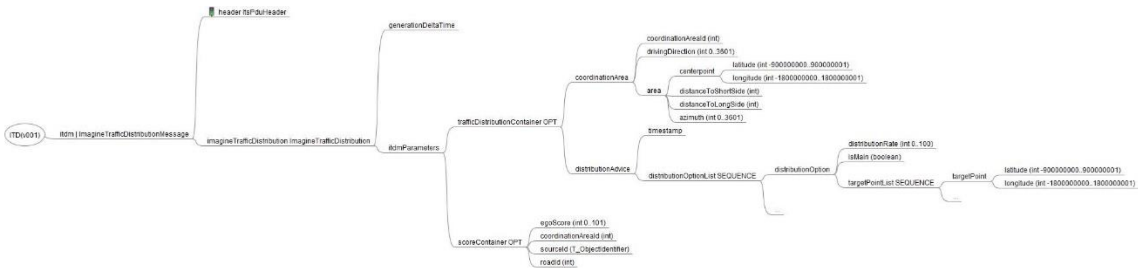


Figure 29: Structure of the ITD message format

Communicate and coordinate route selection (maneuver coordination)

In the fifth step, a vote is held between the participating vehicles on the distribution among the route alternatives. The intention to select a route is based on a score, which is calculated by weighting the different criteria. All criteria (also called parameters) mentioned under "Selecting and defining route selection criteria" are included in the calculation of the score. However, their influence on the score is different and is determined with the weighting. The score thus expresses the route preference.

In front of each decision point where there is a choice between the main route and an alternative route is the voting area (see Figure 30). Each vehicle communicates to the other vehicles in the voting area its maneuver intention based on the score, which in the case of a single decision point is "depart" or "stay on the main route". This happens permanently as long as the vehicle is in the voting area. At the same time, each vehicle receives the planned maneuvers of the surrounding vehicles and checks whether the sum of the planned intentions matches the distribution recommendation. In case of discrepancies, the vehicles with the lowest preference for the route chosen by too many vehicles will choose the changed maneuver first and inform the other vehicles about it. The decision between switching to the alternate route and staying on the main route is ultimately made when the vehicle leaves the voting area.

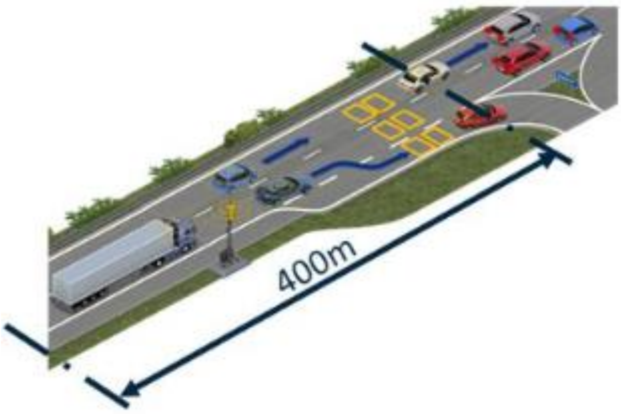


Figure 30: Reconciliation area

Perform maneuvers (maneuver execution)

The driver is informed of the maneuver recommendation via the vehicle's HMI (e.g., "stay on the main route"). The result of the maneuver execution, i.e. whether the maneuver recommendation was followed or not, is implicitly reported back to the SUPS via CAM using the IRS. This information is then taken into account in the following continuous calculation processes.

4 RESULTS FROM CONCEPT VERIFICATION

4.1 Concept verification Continental

Continental dealt with the IMAGinE 2018 cooperation concept on which GUA1 is based. The test system used the GUA1 implementation as a basis, which was enabled to realize the desired scenarios and objects of investigation through extensive further developments of its own.

The resulting maneuver planner is characterized by the fact that it is largely stateless and therefore has virtually no history for ongoing collaborations. In this respect, it is similar to the cooperation concept, which in its pure form is also designed without history.

The length of the generated trajectories is variable in both temporal and spatial terms and depends on the respective situation, or the proximity to potential zones where cooperation could occur. This means that for a subsequent trip on highways or country roads, for example, the planning horizon for trajectories is about 10sec. It is increased up to 30sec when approaching potential conflict zones such as freeway on-ramps or intersections. Increasing the planning horizon makes it possible to start possible cooperation at an earlier stage, which leads to better results for all parties involved. Especially on crowded roads, often the only way to grant a cooperation request is to arrive at the conflict zone a little later by delaying, so that the requestor gets appropriate time to perform his maneuver. For example, in order to arrive one second later at a certain location, the speed has to be reduced much more with a 10sec look-ahead than if 15sec time is available for this. On the other hand, in a longer horizon, more disturbances can occur that prevent the originally planned trajectories from being implemented. However, since trajectories are permanently exchanged according to the cooperation concept, it is possible to react to such disturbances.

The different length of generated trajectories leads to the remarkable effect that subordinate vehicles, e.g. threaders on freeways, initially drive onto the freeway seemingly without conflict and then later still have to cooperate. If, for example, a potential cooperation partner on the main lane of a highway has planned its trajectory only up to the middle of an on-ramp, then a merge-in driver can plan a trajectory without conflict that changes to the main lane at the end of the on-ramp (visually, it looks as if the merge-in driver is "planning around" the trajectory of the other). Only when the trajectory of the later partner is so long that no free maneuvering space remains, cooperation occurs. This effect will be shown in the next section. As a rule, it has no effect on the vehicle behavior perceptible to the occupants.

4.1.1 Sequence of a cooperation using the example of a left turn scenario with the implemented maneuver planner

Continental has verified the concept primarily using a left-turn scenario on rural roads. A simple example will be used to show how the concept works in practice. Three vehicles are involved: The red vehicle R wants to turn left onto the main road, the two vehicles blue B and green G drive straight ahead. The constellation was chosen in such a way that if each vehicle would drive its desired speed, it would lead to a very close approach of green and red. There are three theoretical possible solutions for the situation: red drives through the intersection in front of green, between blue and green, or behind the two.

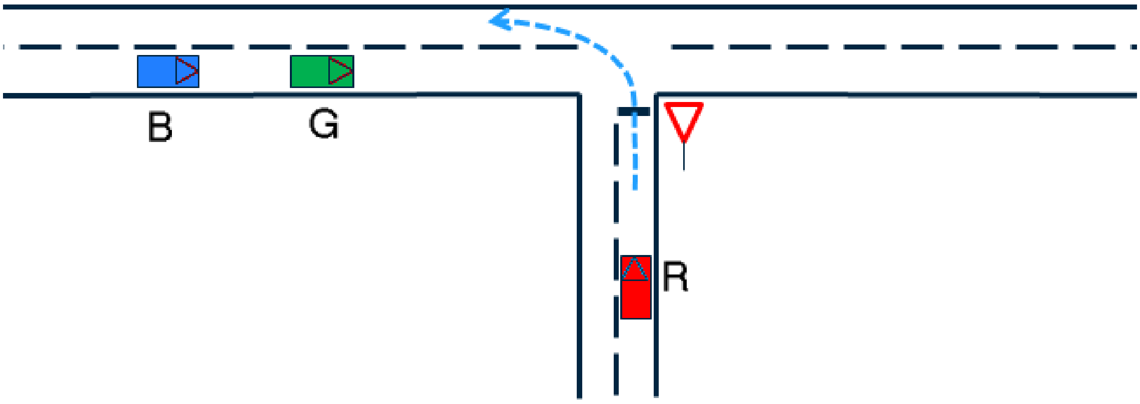


Figure 31: Image of scenario F5.3b: Left turn on rural roads

The diagrams in the following figure show various characteristic values in the course of the combined maneuver. It contains the following data:

- *Velocity*: This shows the velocity progression of the three vehicles. The color scheme is derived from the three vehicles involved. In addition to the strong basic colors, which reflect the requested speed of the trajectories, there are somewhat thinner lines, which reflect the speed converted by the speed controller and the real speed driven. In a perfect controller these would be congruent. Since the implemented system is only a prototype, maneuver planning and trajectory control are not yet well matched in all cases.
- *Requested Trajectory*: This shows the number of requested trajectories sent (from R) and the number of alternative trajectories sent (from B and G).
- *Cooperation Acceptance*: Indicates whether B and G accept the driving maneuver requested by R or not. The value 1 means that they accept the request but do not have to deviate from their selfish goal in order to do so, e.g. because R crosses the intersection far ahead or behind their own vehicle. Value 2 means that they must accept the request and partially deviate from their selfish goals to fulfill it - i.e., in this scenario, they must reduce speed somewhat. It is important to note here that the implemented maneuver planner internally interprets any trajectories from lower-ranking vehicles as demand trajectories (R is required to wait with respect to B and G and is therefore lower-ranking). Since B and G usually fulfill some trajectory of R - i.e. also a trajectory with standstill phase - they usually have at least the value 1. Thus, the value 2 is mainly of interest here, since it indicates active cooperation.
- *Costs*: This diagram shows the additional costs incurred by B and G to fulfill a request from R. The magenta line is the set limit that decides whether a request is accepted.

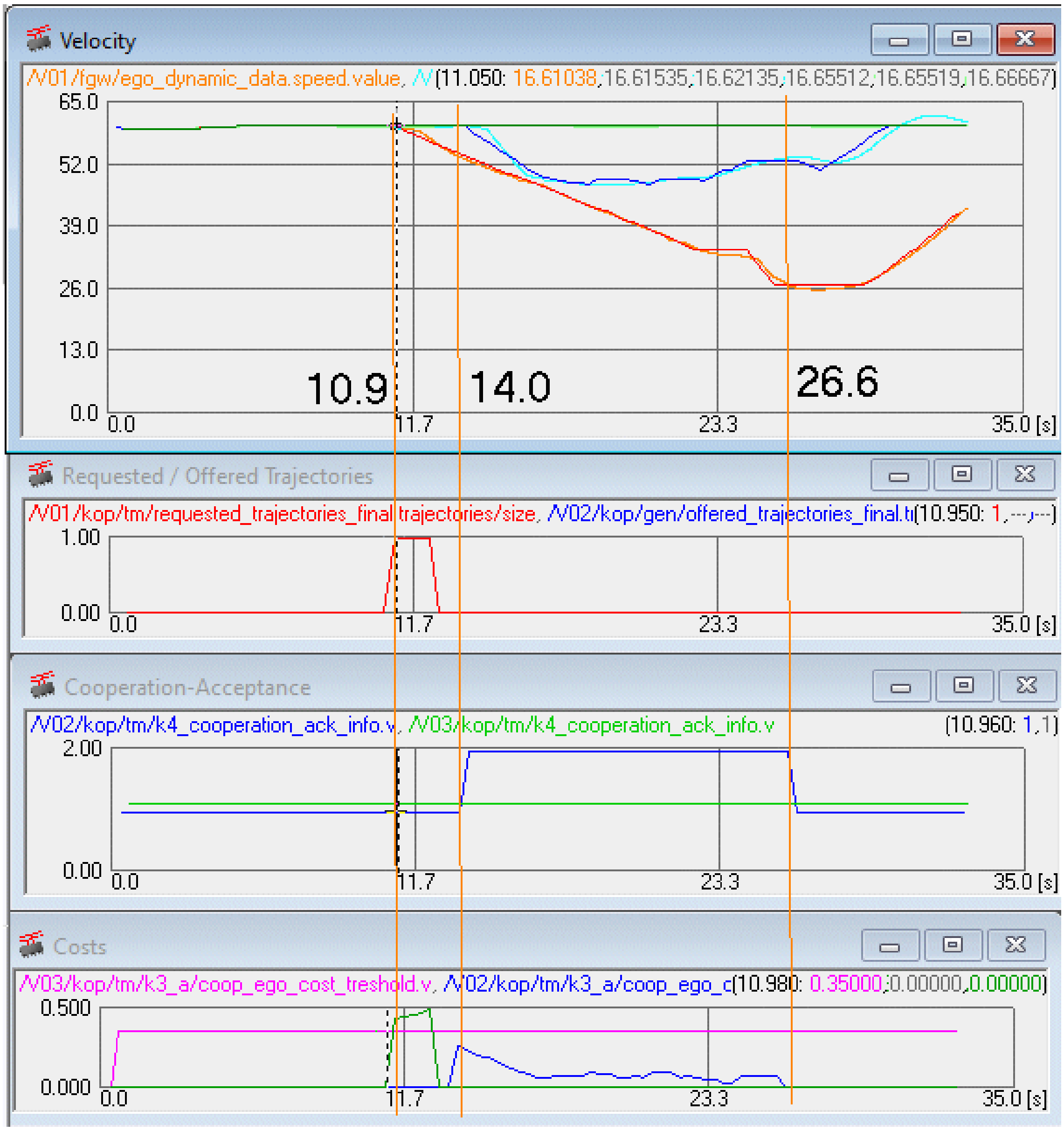


Figure 32: Measurement F5_Scenario3b_V02_Accept_without_Drv_2021-11-14-53-20_ok.bag resulting from CarMaker Simualtion of F5-Scenraio 3b, test run "V02 AcceptWithoutDrv".

The maneuver sequence now looks like this:

First, the vehicles approach the intersection uninfluenced by each other. The reference speed (=SetSpeed) is 60kmh for all of them. At time t=10.9sec, R detects that it is approaching an intersection and the received trajectories of the vehicles on the main lane no longer allow the desired trajectory. It sends a demand trajectory to indicate its own need to improve the situation. It sends the trajectories from the following figure. It contains the reference trajectories for all vehicles marked in color. For vehicle R, two trajectories are shown here. The red one shows the demand trajectory and the magenta one the reference trajectory that the vehicle is forced to drive so far. The demand trajectory would allow the vehicle to cross the intersection several seconds earlier. It can be seen that B's blue reference trajectory is significantly shorter than the others' because B has not yet assessed the intersection as a potential conflict zone for himself.

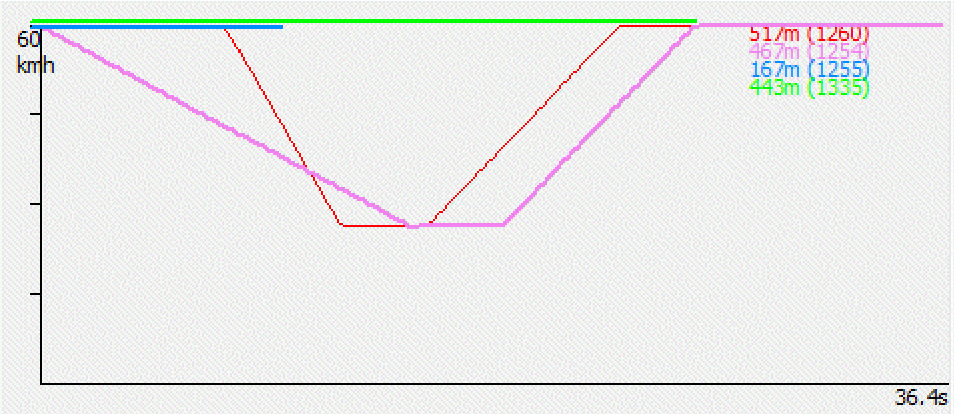


Figure 33: Velocity profile of the trajectories at time t=10.9s

Vehicle G receives the demand trajectory and calculates internally what costs would be incurred to fulfill it. However, as the *costs* diagram shows, these costs are above the defined threshold. Thus, G rejects the fulfillment of this demand and accordingly stays with its previous reference trajectory.

Consequently, vehicle R cannot implement its demand and is forced to cross the intersection behind G. The vehicle R is not aware of whether the other vehicles have received its demand trajectories and reacted to them. Since it does not know whether the other vehicles have received its demand trajectories and reacted to them, it sends the demand trajectory for a while. After about 1.7sec the implemented maneuver planner of R assumes that G is not ready to enable the desired maneuver and stops sending further demand trajectories.

At time t=14.0sec, B also recognizes the potential conflict zone and its maneuver planner extends its trajectory horizon to the intersection. In doing so, it realizes that R's reference trajectory prevents its own selfish intentions - the trajectories would intersect. A conflict arises. The solution possibility provided according to the cooperation concept would be to send the conflicting reference trajectory with the knowledge of its own priority according to the StVO anyway. Thus, the recognized conflict would be sent to the outside. R would have to react to this and adjust its reference trajectory and send a demand trajectory instead (provided R has the same view of its own subordinate priority according to StVO). However, the implemented maneuver planner is able to optimize this process. As mentioned above, it internally treats each trajectory from R as a demand trajectory. Therefore, the trajectory sent by R so far is already evaluated with respect to a possible granting of cooperation. In this case, this assessment is positive, since the costs incurred by the necessary delay to approx. 50kmh are considered to be acceptably low. Thus, the own reference trajectory is proactively adjusted and dispatched. The trajectories from the next figure are created. In the diagram Cooperation-Acceptance you can see how the value jumps to 2. The cost value of B is recognizably below the threshold.

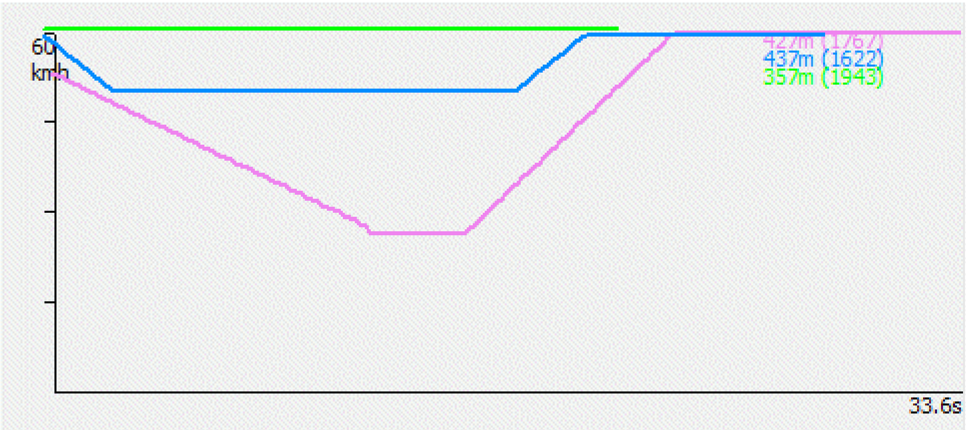


Figure 34: Velocity profile of the trajectories at time t=14.0s

At time 26.6sec, the resulting maneuver is completed to the point where R has reached the intersection. B can again plan a trajectory going back to its original speed. The value in the *Coopertation Acceptance* diagram goes back to 1. The entire maneuver from B's point of view has taken about 14sec.

The velocity progression in the *Velocity* diagram over the maneuver duration shows that the trajectory originally planned (t=14.0sec) by B for the cooperation was not quite adhered to. Already before 26.6sec it increases its velocity slightly. Since, on the one hand, R's speed at the beginning of the maneuver temporarily dropped to 48kmh, and, on the other hand, R was apparently able to drive somewhat faster than planned and this is evident from the continuously exchanged reference trajectories, B can already adapt to a somewhat faster trajectory at an earlier point in time.

Note: In principle, the negotiation phase at the beginning of the cooperation is problematic due to the latencies that occur. A's requests are based on B's reference/alternative trajectories, which are e.g. one cycle=333ms old. Until B in turn evaluates the demand trajectory of A, another e.g. 333ms pass. Thus, since an alternative trajectory was originally sent and acceptable to B, a total of 666ms have passed, which accordingly leads to higher - possibly too high now - costs for B. This is because during this 0.666sec, B has continued to travel at its current speed. Tendentially, A will request less than B then has to grant - if in the course of the corresponding trajectories a constant speed is not provided for the assumed duration of the negotiation phase. The latter is not the case in the current implementation.

4.1.2 Involvement of the driver or a higher decision-making authority

The decision process on whether to grant a cooperation request is two-stage in the implemented maneuver planner. The first stage uses a cost assessment to decide whether the cost of the altruistic maneuver compared to the selfish solution is below a defined threshold. The second stage decides whether the required maneuver requires such major changes that a higher decision-making authority - human or machine - must give its approval. Major changes are, for example, a lane change or a significantly reduced speed.

The following scenario describes possible effects if obtaining the additional consent is required and correspondingly additional time is needed for this - more for a human driver than for a machine driver. Here, a time delay for the consent of a cooperation of one computation cycle = 0.33sec is assumed. The scenario is the same as described in the previous section, except that the starting position of the rear vehicle B has been moved slightly forward (5m = 0.3s at 60kmh). Thus, B must reduce speed more to create the same free maneuvering space for R.

The first phase, as long as B is not yet involved, is exactly as described above. But when B recognizes the intersection as relevant and the decision on the implicit demand trajectory is pending, this time the required change is so large that the internal higher authority is consulted for approval. During this internal process, the selfish trajectory continues to be sent, now in conflict with the trajectory sent by R.

R recognizes the conflict and - since R is subordinate according to StVO - it reacts according to the concept by planning a reference trajectory that crosses the intersection behind B and G and additionally dispatching a demand trajectory that wants to cross between both.

The following image shows the time when B has already responded positively to the reported demand of R, but R has not yet received and processed this. Due to the additional internal tuning time required (0.33sec) and the position shift (equivalent to 0.3s), B's required speed for granting cooperation decreases to 48km/h. We can also see that R's demand trajectory is different from the previous case. In the previous case, her goal was to get G to let R cross beforehand. Here the goal is to cross behind G but in front of B.

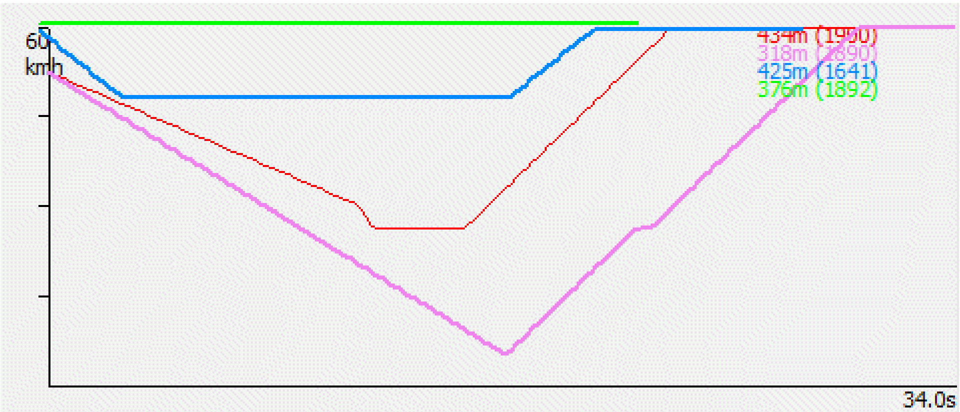


Figure 35: Trajectories at time t=13.7s

The following diagram shows some parameters of the modified maneuver. In addition, a diagram *Cooperativeness* has been added, which shows whether R considers the other vehicles as willing to cooperate or as refusing. Also, a diagram *Driver-Acknowledge, which shows* from B and G whether the higher authority is asked to agree, which is the case in this scenario at 13.7sec. At 13.3sec, the value for Cooperation-Acceptance at B briefly goes to 0, because here B has consciously chosen the selfish trajectory as long as the process of coordination with the higher instance is ongoing.

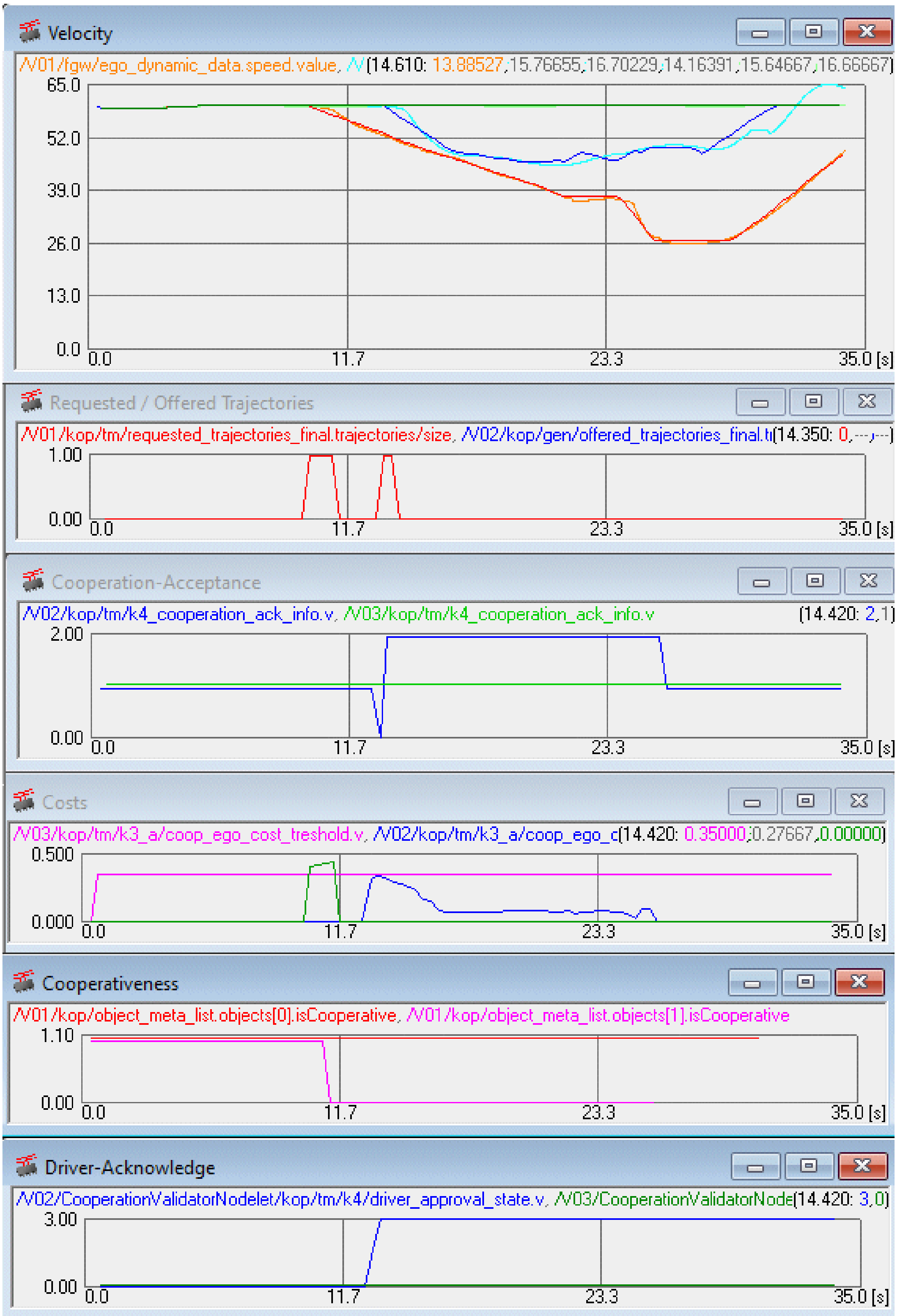


Figure 36: Measurement F5_Scenario3b_V02_Accept_by_Drv_2021-11-11-15-12-08_ok.bag resulting from CarMaker simulation of F5-Scenraio 3b, test run "V02 AcceptByDrv".

4.1.3 Simultaneous cooperation with two partners

In the intersection, situations can occur where two vehicles must simultaneously accept a cooperation request from a third party before it can come about. This is outlined, for example, in the following picture, where B and G must agree so that R can cross the intersection in front of both of them and merge in front of G.

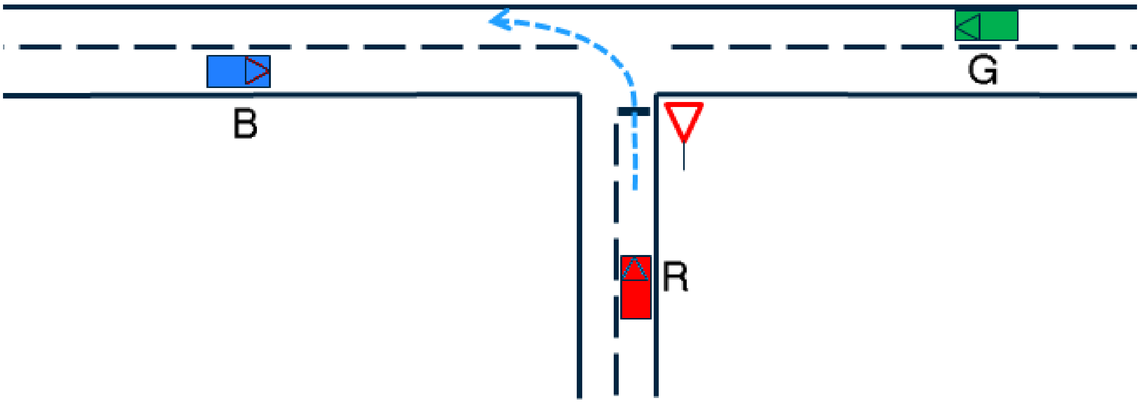


Figure 37: Image of scenario F5.3: Left-turning on rural roads, two vehicles from the right and the left

Here, both B and G have to step in advance and enable the cooperation on their own, without knowing whether the other necessary vehicle will ultimately agree to this as well. In the investigated cooperation concept, the effective and more reliable solution of such situations is enabled by the alternative trajectories. Using these, one vehicle can tell the others what interventions, if any, it would be willing to make to enable a need for cooperation. If these are sent, then in this case B and G, respectively, know what the other is willing to do and can accordingly initiate the interventions to grant cooperation from their side with more certainty or even refuse to do so for the time being.

The following figure compares two simulation runs, where the left half shows a case where alternative trajectories are sent, while the right half does not. Since the implemented maneuver planner always uses the reference trajectories of all other vehicles when fulfilling foreign demand trajectories, it cannot find a conflict-free solution to the overall situation without alternative trajectories (the foreign reference trajectory is in conflict with the foreign demand trajectory), thus B and G block each other and no cooperation with R is achieved. It can be seen that the speed of B and G remains constant in this case, which means that the occupants of the vehicles will not feel any effect of the failed attempt at cooperation.

Alternative implementations could carry out a (possibly time-consuming) situation analysis from the perspective of the required second cooperation partner or even dispense with the condition of the external reference trajectory. The latter, in turn, could lead to unnecessary interventions in one's own vehicle management or - in other situations - to the granting of requirements that cannot be realized due to the overall situation.

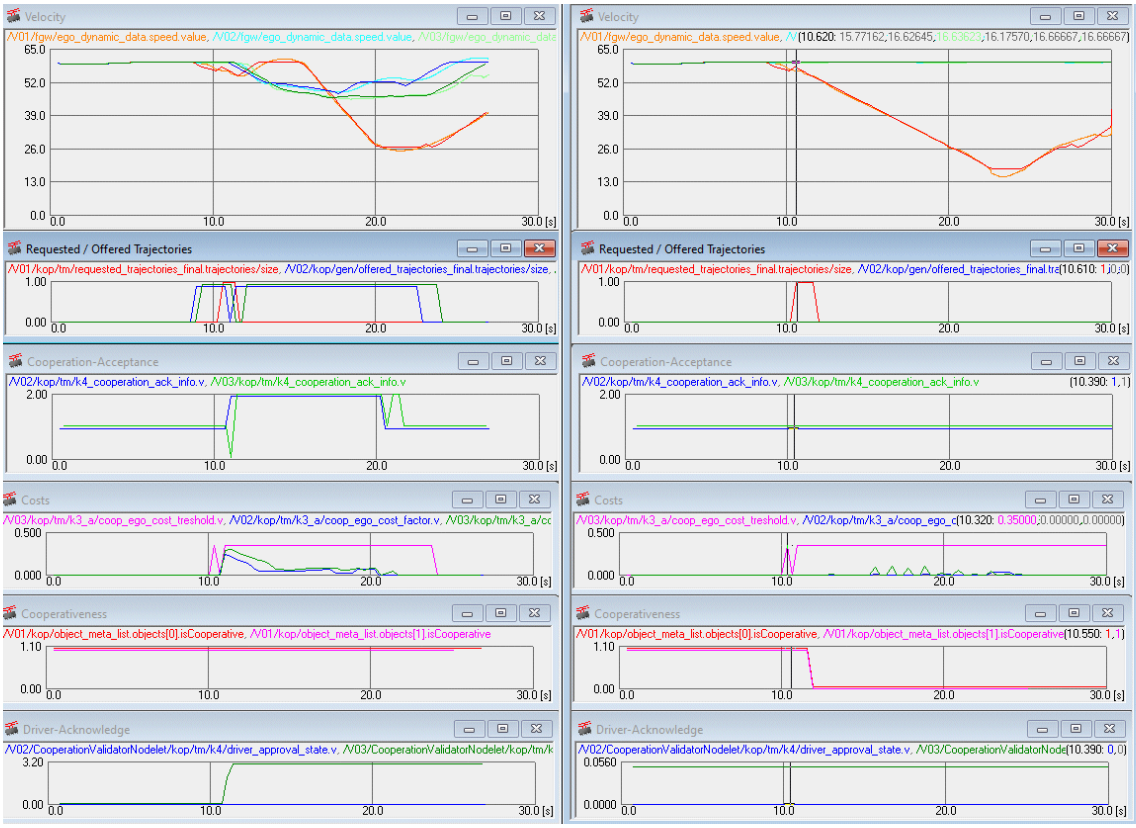


Figure 38: Measurement F5_Scenario3_2021-11-09-19-35-32_both_same_ok.bag vs. F5_Scenario3_2021-11-09-19-33-46_both_same_nok_noOffer.bag; resulting from CarMaker simulation of F5 scenario 3, test run "Both same".

4.1.3.1 Effect of incorrect alternative trajectories

On the other hand, even alternative trajectories do not provide absolute certainty that cooperation between all partners involved will be achieved. The effect of wrong trajectories in the implemented maneuver planner (or in others the effect of the wrong estimation of the willingness of other cooperation partners) can be seen in the following course in the same scenario.

In this case, B sends alternative trajectories that it itself rejected during the cooperation evaluation. Vehicle G is itself willing to enable R's demand and assumes, based on the alternative trajectory, that B is also willing to do so. Therefore, G adjusts its reference trajectory and slows down. However, B does not implement the transmitted alternative trajectory and consequently R cannot turn in front of both vehicles as desired, but continues to transmit demand trajectories. Until the time 11.6sec G waits for B to accept the cooperation. Only then G gives up the cooperation (=the implemented maneuver planner does not receive any suitable alternative trajectories from B anymore) and goes back to its own egoistic trajectory.

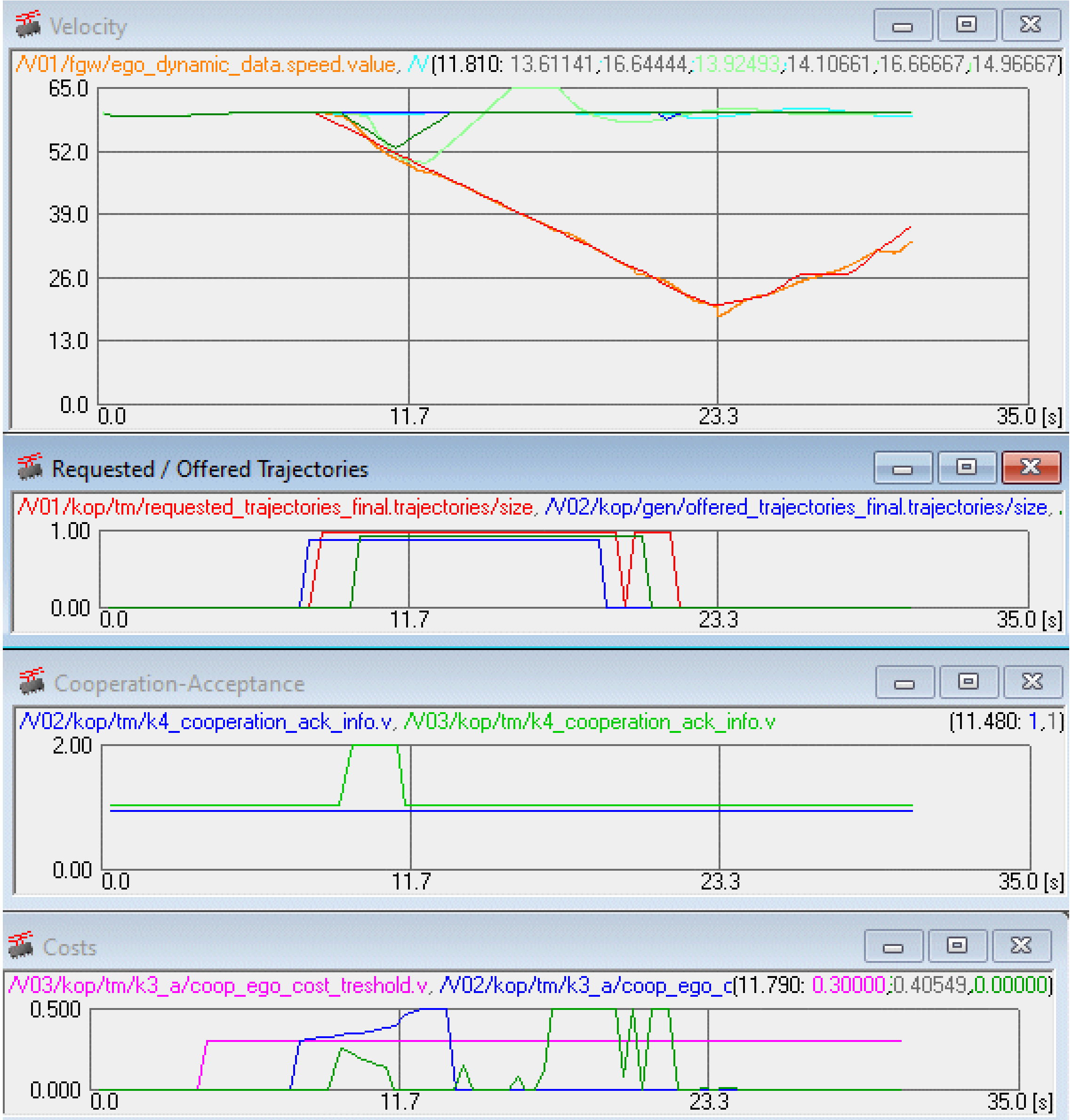


Figure 39: Measurement F5_Scenario3_2021-10-27-16-39-46.bag; F5-Scenario 3

4.1.3.2 Time-delayed cooperation with two required participants

Using the described scenario, where two vehicles B and G from the right and left have to agree to a cooperation request from R at the same time, the effect of delayed rejections by relevant participants can be shown as an example.

Here, the configuration was chosen in such a way that G does not recognize the relevance of the intersection situation at the same time as B, but somewhat later. G has a somewhat shorter planning horizon than B.

B - uninfluenced by the short trajectory G - first responds to R's request and delays accordingly. Shortly thereafter, G with its planning horizon also recognizes the relevance of the situation and evaluates the implicit demand trajectory of R. This decision is negative here, i.e. G maintains its speed. Thus, the cooperation between R and B is also no longer feasible. It is aborted at about t=9.8sec.

The velocity curve shows that B has already decelerated in accordance with its consent and then accelerates back to the initial velocity after G rejects it. G, on the other hand, drives through at constant speed. R maintains the speed until 9.8sec and then has to brake to let B and G pass.

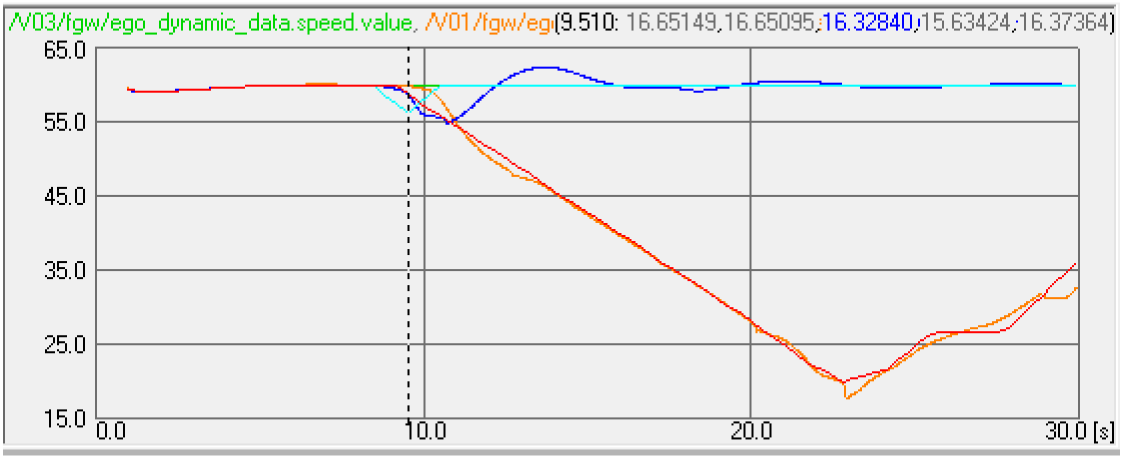


Figure 40: Measurement F5_Scenario3_2021-10-27-20-43-46_second_aborts.bag, based on Carmaker scenario F5-Scenario3

4.1.4 Recognition of the cooperativeness of other participants / impact of poor trajectories of demand

In the case of several possible cooperation partners, it is essential which vehicle is implicitly addressed for the implementation of an own demand. In the previous scenarios F5.3b the front vehicle G was addressed first and after its rejection the rear vehicle B. This was possible because the implemented maneuver planning integrated a detection of the cooperativeness of the possible partners. This tries to recognize from the course of the sent demand and received reference trajectories whether a vehicle is willing to grant its own demand or not.

The case of several possible cooperation partners arises, for example, if there are strongly different planning horizons. If they are similar, there will often be only one partner, because the trajectory of the second one has not yet reached the conflict zone. In the case of function F1, for example, there is usually only a relatively narrow range of variation where vehicles can merge.

Without such a detection, R would send a long time the trajectory that allows him to cross in **front of** G and B. Because from R's point of view this is a possible and - according to his estimation - acceptable possibility for the others.

An estimation of how far foreign vehicles would go to fulfill one's own wishes is difficult and error-prone. Therefore, additional detection of whether foreign vehicles reject one's own demand trajectories or not helps here. The effect if such detection is missing is shown in the following figure. In the diagrams on the left side the implemented detection was active. In the diagrams on the right side it was switched off.

It can be seen that the intervention of B instead of at 9.3sec only occurs at 14.0sec and thus correspondingly stronger. The scenario did not fail here only because R at some point considered the costs for G to be too high and addressed B after all. And because at this moment the costs for the now more violent maneuver at B were just acceptable.

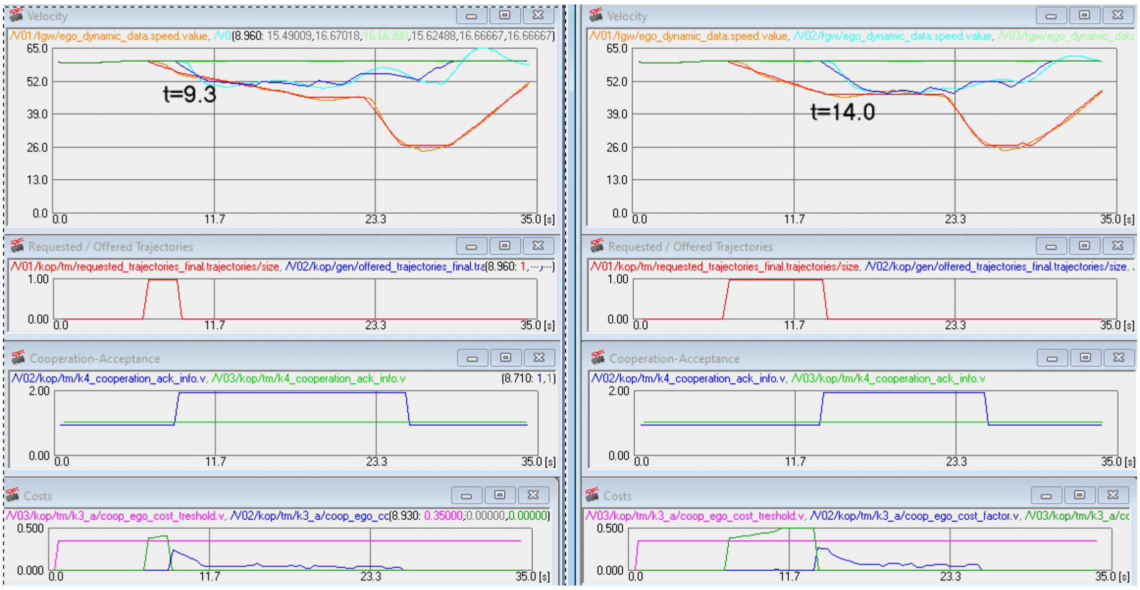


Figure 41: Measurement F5_Scenario3b_V02_AcceptByDrv_ok_2021-11-15-16-10-47.bag vs. F5_Scenario3b_V02_AcceptByDrvNoMeta_ok_2021-11-15-16-12-30.bag; F5 scenario 3b, test run "V02 AcceptByDrv".

However, detecting whether another vehicle has accepted or rejected a trajectory is difficult because, for one thing, the reactions may be small. For this, there may be a different understanding of whether a demand has been accepted or not, as there may be a different understanding of whether a solution is conflict-free or not - e.g., whether contained safety distances are acceptable or not. In addition, due to the stateless protocol, latencies in processing (see also keyword driver involvement) and possible transmission errors, it is not clear if and when a vehicle has received its own trajectory and included it in the planning.

To counteract this problem, the deliberate rejection of received demand trajectories was also transmitted via the protocol so that the original sender can exclude possible partners more quickly and reliably. In other words, the ID of the foreign demand trajectory was also sent in the sender's own MCM. This resulted in significant improvements in terms of recognition quality and speed. This had a positive effect on the cooperative handling of the scenarios presented - especially when there are many vehicles on the main roadway and many possible cooperation partners.

Note: the conscious acceptance of foreign (demand) trajectories was also transferred (in case of active cooperation). However, this had only the reason of easier evaluation and was not used by maneuver planning.

4.1.5 Interference

Here, the effects of two possible disturbances are considered as examples.

- Cooperation grantor withdraws its consent during an ongoing cooperation
- cooperation can no longer be carried out because of an external disturbance
  - here using the example of a human driver who intervenes in the previously (partially) automated system.

Not particularly considered, for example:

- increased latencies
  - Latencies can be different depending on the radio technology used, e.g. LTE vs. 802.11p.
  - The latency in the simulation was 330ms (=1 cycle) for the transmission, 660ms for the response to an own transmission.
  - The effects should be similar to those in the subchapter "Involving the driver or a higher decision-making authority". Critical is the phase of coordination (risk of failure due to too late reaction) and the reaction to unexpected events.
- Communication breakdowns
  - At the moment of occurrence, the effects should be similar to increased latency.

4.1.5.1 A commitment to cooperate is later withdrawn

In this case, the cooperation comes about as described above. R makes his request, B agrees to it after reassurance with the higher instance. There is one more transmission from R, because the safety distances are still a bit too narrow for R, but then the cooperation is stable and the trajectories are driven as planned. At the time t=22.1sec, however, B now withdraws its original commitment for some reason. This can be seen in the Cooperation-Acceptance diagram, where the value for B decreases from 2 to 0. R receives the new reference trajectory and realizes that it can no longer pursue its own preferred trajectory. Thus, R switches to a trajectory that makes it brake hard, wait, and then cross the intersection behind R and G (see kink in the velocity trajectory), and sends out demand trajectories again to establish new cooperation. However, this is not accepted by B. As a result, R then classifies B as non-cooperative and stops sending further demand trajectories. The maneuver ends uncooperatively but without an accident.

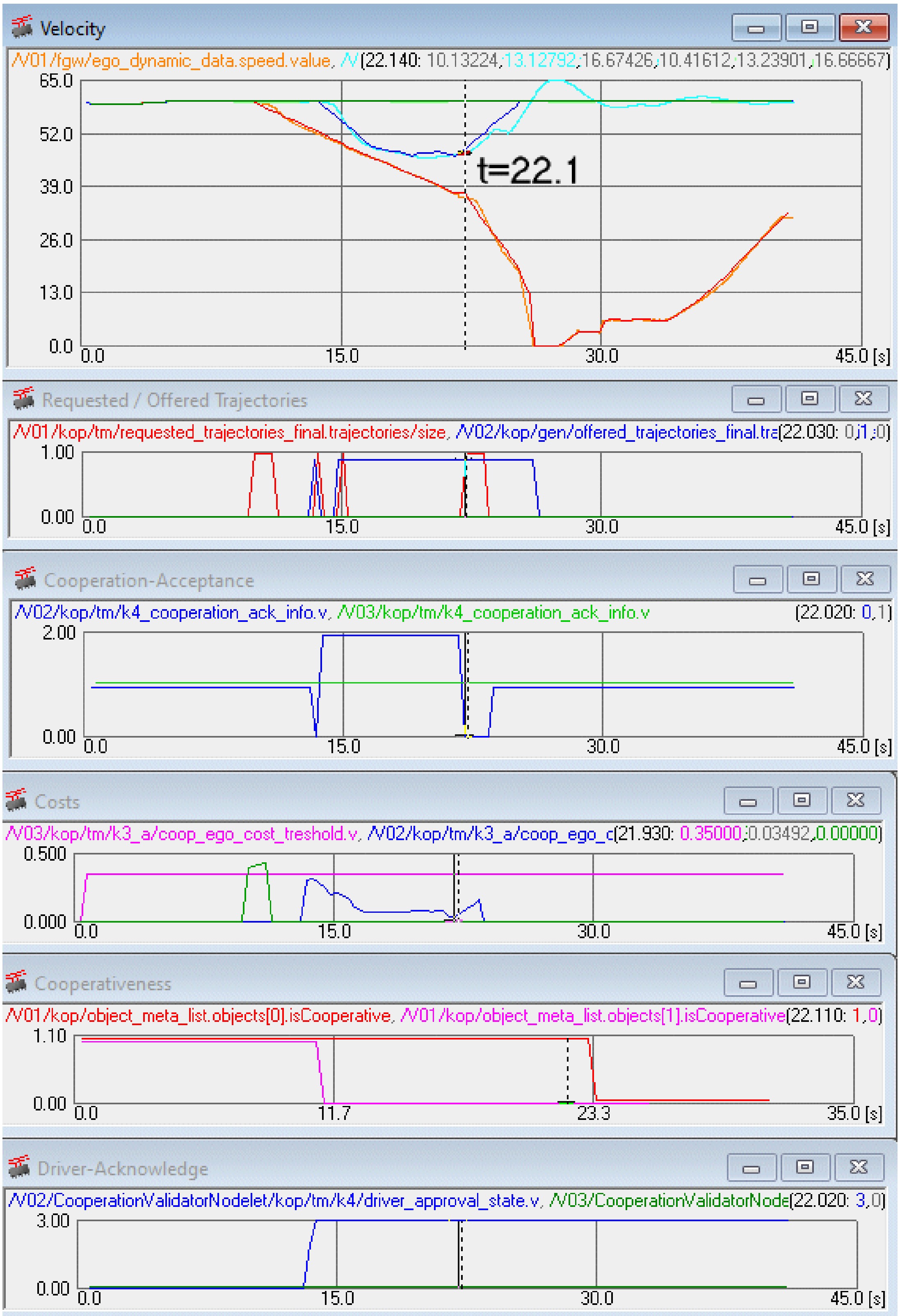


Figure 42: Measurement F5_Scenario3b_V02_AcceptByDrvAcc_2021-11-18-11-34-26_acc.bag; F5 scenario 3b, test run "V02 AcceptByDrvAcc".

4.1.5.2 Manual driver intervention interferes with other cooperation

Here it is assumed that vehicle G, which is not involved in the cooperation according to the previous pattern because it has rejected it, suddenly brakes - e.g. because its driver intervenes in the system. This happens in the simulation at time t=17.8sec. The cooperative maneuver planner of G detects the driver intervention and now sends a trajectory that it estimates from the driver behavior. In the current implementation, this estimate is based purely on the measured longitudinal vehicle deceleration for simplicity. This longitudinal deceleration is continued for 3sec before a constant speed trip is then assumed. Since the longitudinal deceleration follows the braking intervention of the driver with a delay, it takes accordingly until the estimated driver trajectory also reflects the deceleration.

At time t=18.8sec, R realizes that it cannot perform the desired maneuver as planned. It switches to a trajectory that would let it cross behind G and B and sends a demand trajectory for new cooperation. B, on the other hand, recognizes that G is decelerating, and in turn decelerates - albeit slightly less, since low velocities at a constant temporal distance mean a smaller spatial distance. The new demand trajectory of R is not fulfilled due to too high costs for its fulfillment (see peak in the diagram *costs*).

At time t=19.5sec it is obvious from the trajectory of G for R that it can now cross the intersection before G and B - which corresponds to the preferred solution for the maneuver. Therefore, it plans a trajectory that approaches the intersection as efficiently and quickly as possible. At the same time, this removes the reason for continuing to send demand trajectories.

The following images show the signal waveform for the simulated scenario and the individual trajectories just before t=17.8sec, at 18.8sec and after 19.5sec.

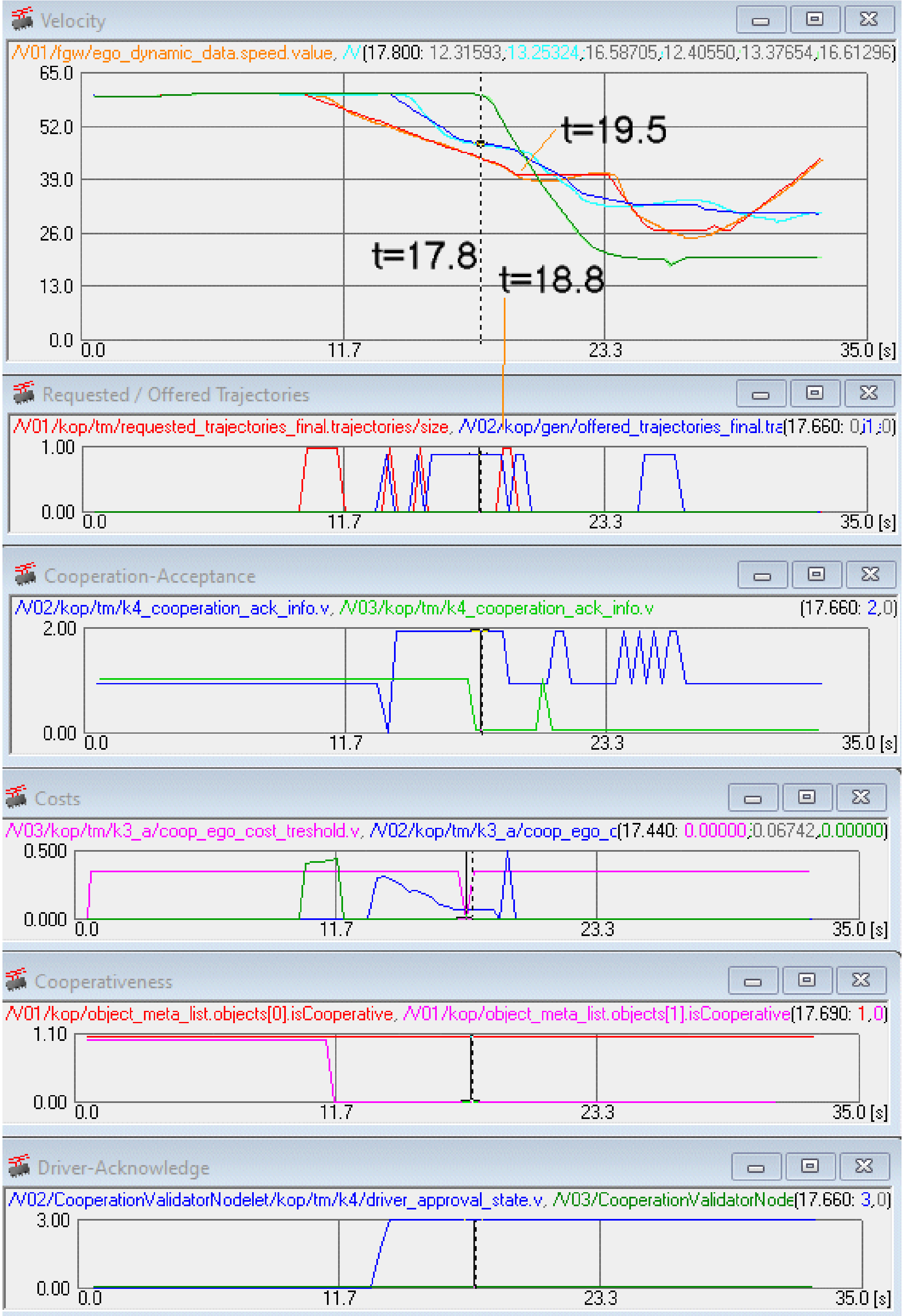


Figure 43: Measurement F5_Scenario3b_V03_manualBrake_2021-11-16-18-35-35.bag; F5 scenario 3b, test run "V02 AcceptByDrv".

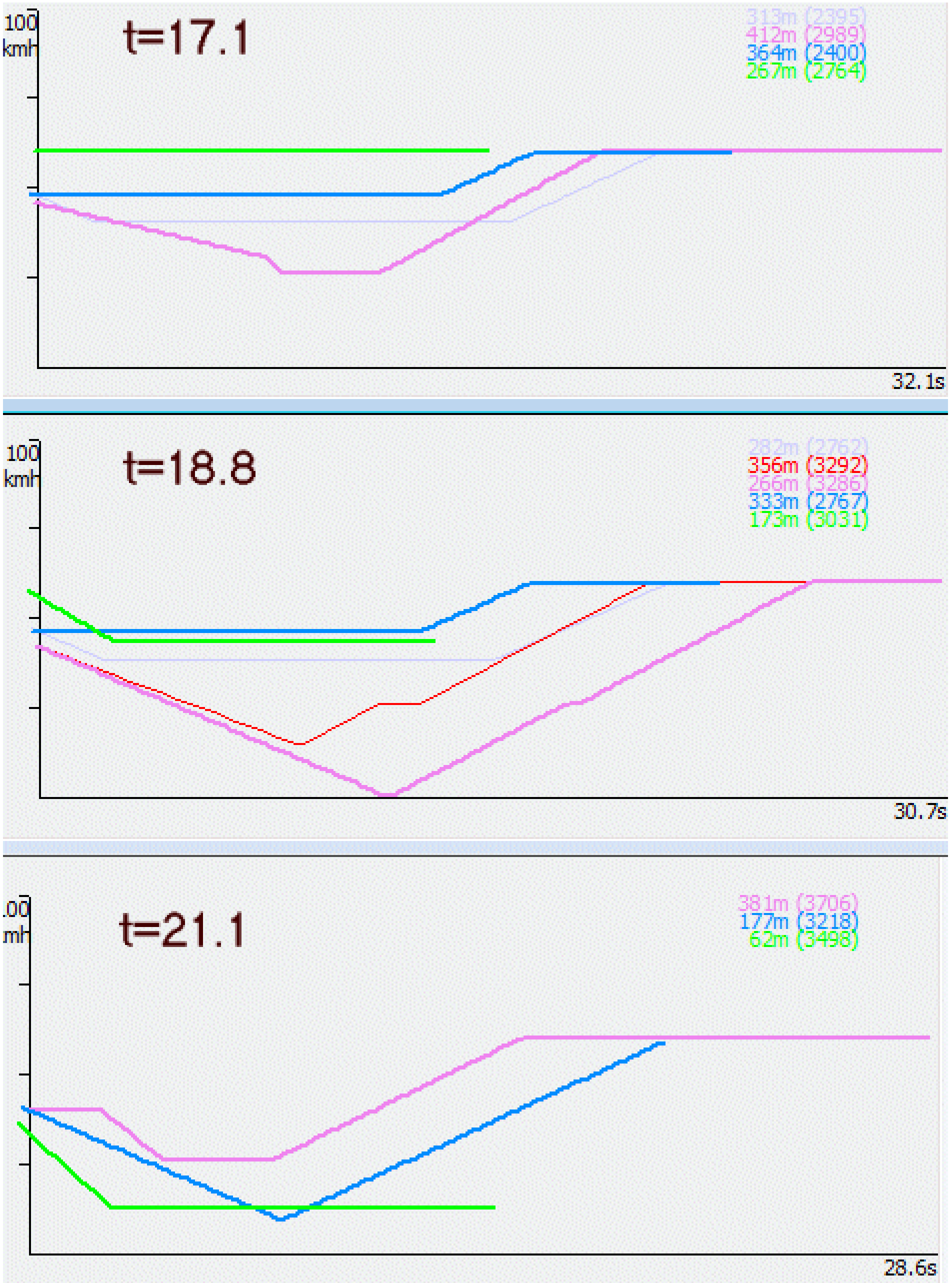


Figure 44: Trajectories for three selected time points

4.1.6 Nested cooperation using the example of a freeway access road

In the following, the course of several nested collaborations in a more complex situation is described as an example. Here, two different collaborations must be performed to solve a situation.

The picture shows a typical highway situation. Vehicle R (red) wants to enter the highway. Vehicle O (orange) is so far ahead that R has to merge in behind it. Cooperation with vehicle B (blue), on the other hand, is helpful so that R can merge in between B and O. To keep the cost of cooperation acceptable for B, B wants to change lanes to the left lane. However, this is blocked by the vehicle G (green) driving on the left. Consequently, G would have to drive a little slower to allow B to change lanes, which means that now G and B also have to cooperate.

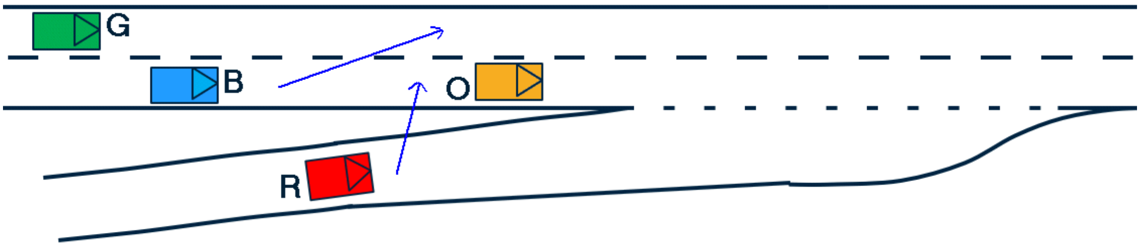


Figure 45: Scenario F1 Motorway access

The following two diagrams show the signal progression, with the second magnifying the time segment in which the actual cooperative tuning takes place. At time t=10.2sec, R recognizes its need for cooperation and sends a demand trajectory for B. At t=11.2sec, B has received the request and now in turn sends a demand trajectory to change lanes to G. Since in the current configuration the cost threshold for B to let an R merge in front of it even by driving slower was just acceptable, R can already convert its demand trajectory into a reference trajectory and perform the desired maneuver. In a different configuration, B would continue to send its selfish trajectory and thus R would not yet be able to perform the desired maneuver either.

At time t=12.5sec, B has received confirmation from G that B can also perform his lane change and thus stops sending his own demand trajectory. This actually clarifies the situation between all parties involved.

However, the in-vehicle coordination within B now takes place, during which the higher-level vehicle system is requested to approve the intended lane change. Due to the current implementation of the cooperative maneuver planner, B temporarily sends its selfish trajectory during this time, which denies R its requested maneuver. Thus, R has to send a demand trajectory again and G also switches back to its old trajectory. As a consequence, this means that B also has to send a demand trajectory again for its lane change. A more clever implementation of the maneuver planner, where the internal system back-up takes place e.g. in parallel or before, would avoid this double coordination with other vehicles.

The cooperative coordination between the vehicles starts approx. 16sec before the lane change of R is practically executed. This allows the cooperating vehicles to build up sufficient safety distance before, for example, a lane change takes place.

Note: The valley in the speed curve of R is mainly caused by the fact that after the first acceleration phase R comes to the curve to the freeway slip road and, in order not to let the transverse acceleration become too great, only drives through it at approx. 60kmh. The lateral acceleration permitted by the configuration is not fully utilized in order to reach the intended position behind vehicle O.

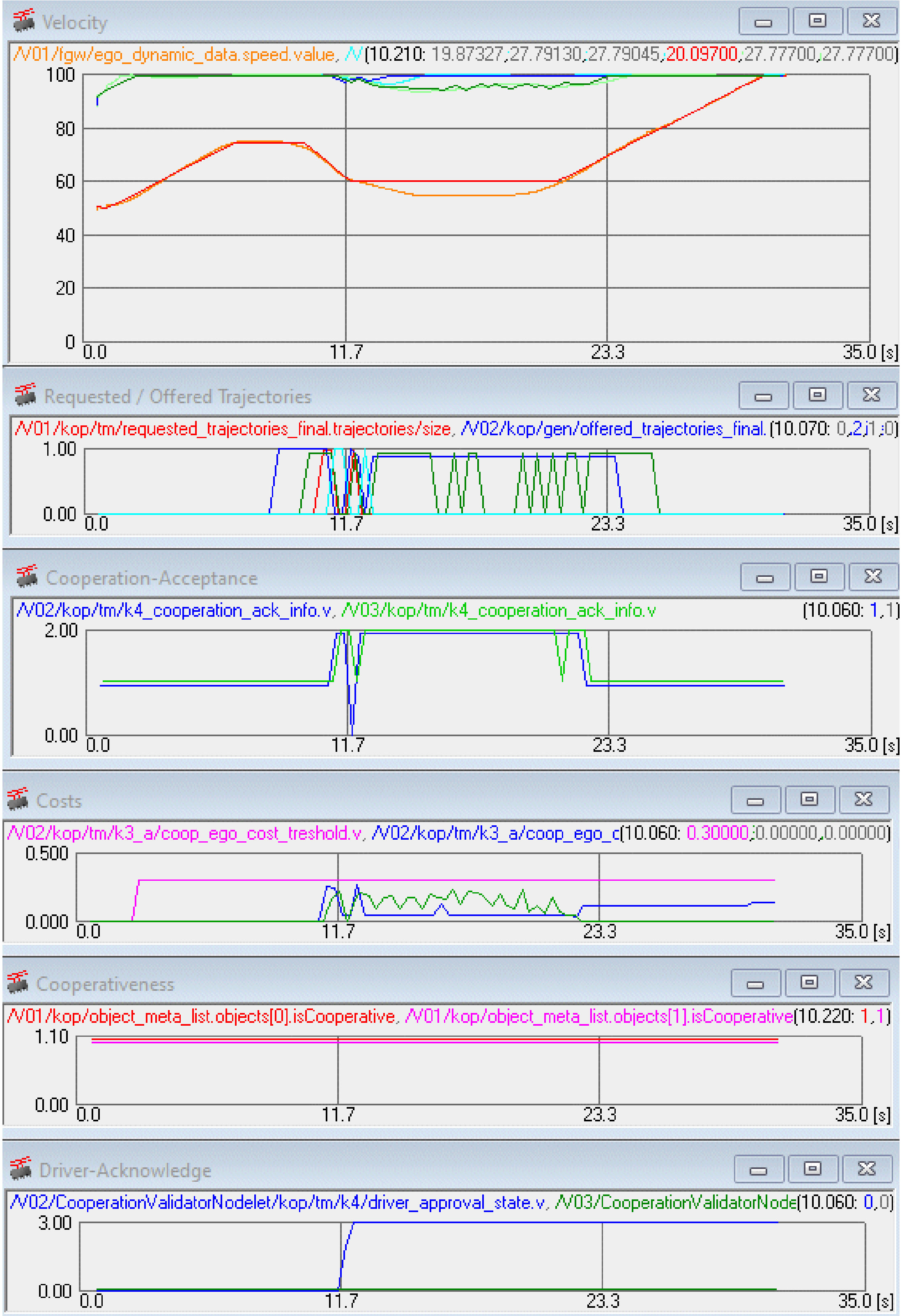


Figure 46: Measurement F1_Scenario3_Traffic_Standstill_2021-12-20-15-42-17_four.bag, test run "Standstill

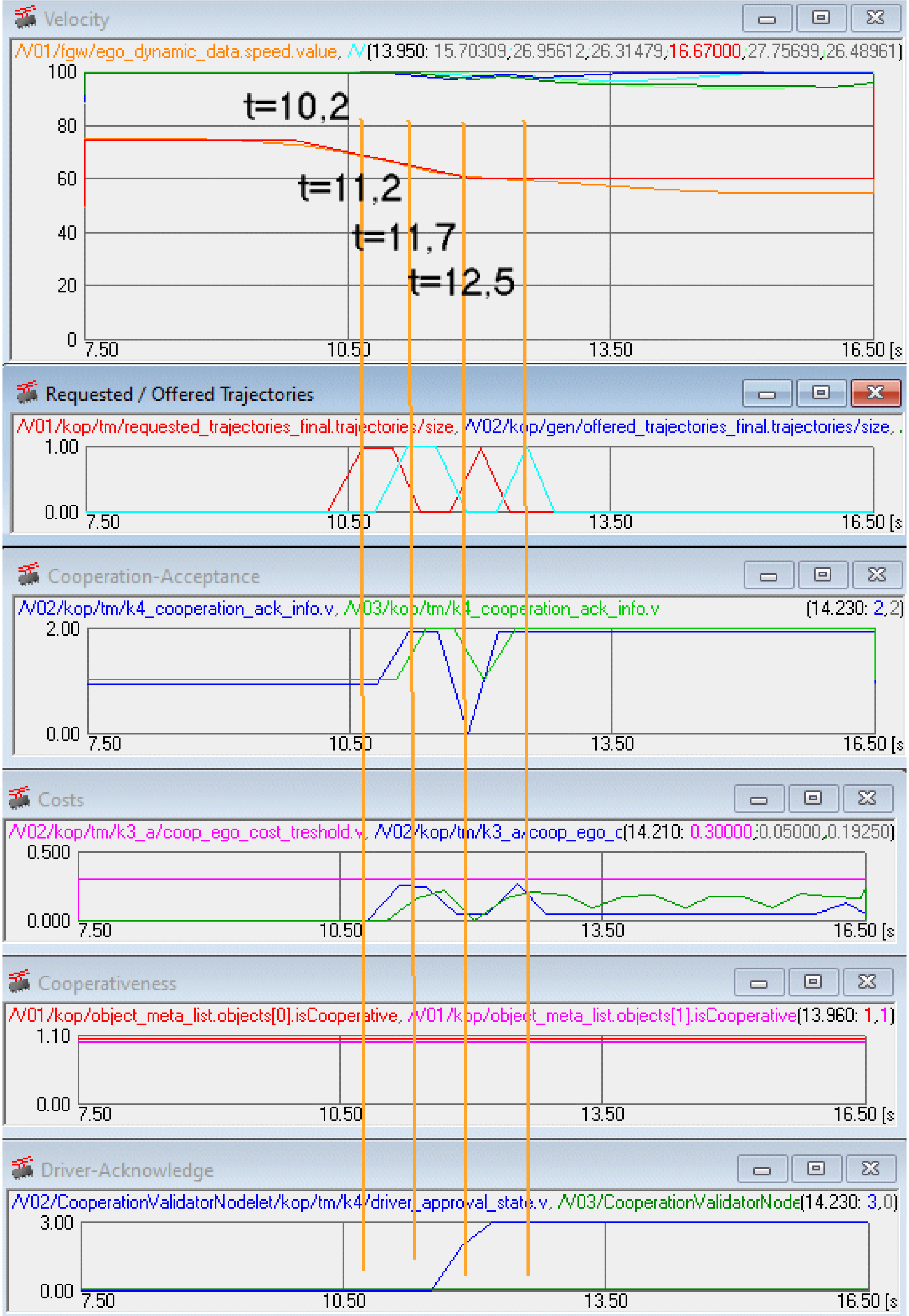


Figure 47: Extract from measurement F1_Scenario3_Traffic_Standstill_2021-12-20-15-42-17_vier.bag, test run "Standstill

4.1.7 Long vs. short planning horizon / coordination lead time

In the previous setup, the planning horizon and accordingly the time at which the vehicles coordinated cooperatively was about 16sec before the actual lane change. This allowed the cooperating vehicles to build up sufficient additional safety distance in advance. Vehicle G had to reduce its speed only slightly from 100km/h to approx.95km/h. Vehicle B was able to maintain 100km/h.

Long prediction/planning can be difficult to realize in practice with dynamic traffic events. Therefore, the following image shows the speed history of the vehicles involved, with the horizon reduced to 9sec with all other parameters unchanged. This corresponds approximately to the position where R could first see the rear traffic in his rearview mirror. It can be seen that cooperation is now not forthcoming. Consequently, R has to slow down to 50kmh to get in behind B. The reason is that B cannot build up a sufficient gap in time within his acceptable possibilities.

Note: The small peak in the velocity curve of R at approx. t=18sec is due to the fact that only at this moment the implementation recognized the situation "highway approach" and from then on more suitable trajectories were preferred.

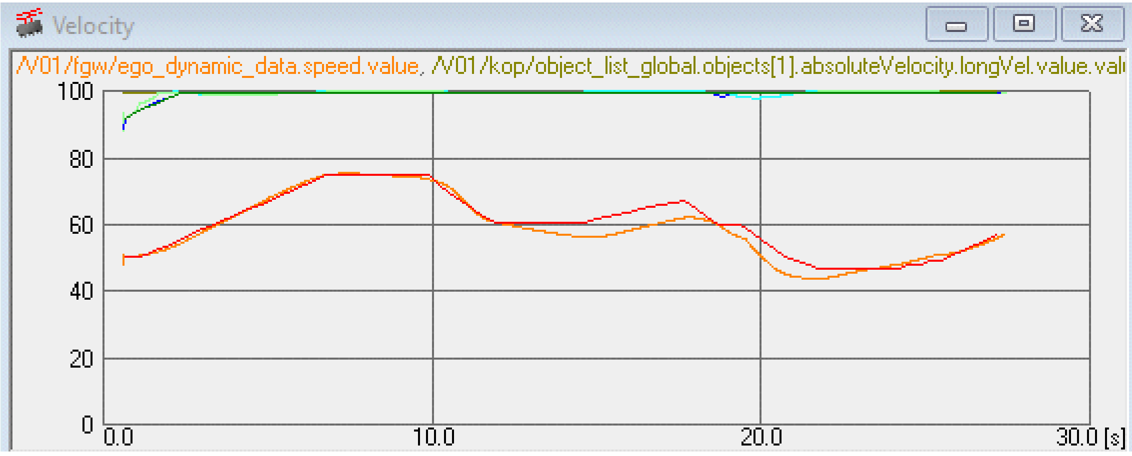


Figure 48: Shortened preview time. Cooperation fails. Messung F1_Scenario3_Traffic_Standstill_2021-12-20-19-15-28_short_fail.bag

In real road traffic, such situations are usually solved by shortening the safety distances by the threader for the moment of the turn-in, e.g. from normally 2sec ("half speedo") to 1.2sec In the following picture, you can see the speed progression after the configuration has been adjusted accordingly. Since the maneuver planner is parameterized very cooperatively, the cost limit of B was not yet reached here. Compared to the longer planning time, vehicle B has to reduce its speed much more, from 100 km/h to 90 km/h for about 5sec. This may have a stronger impact on the following traffic. The TTC (time-to-collision) is shown in the following picture. You can see how B steadily increases the gap from the beginning of the cooperation to let R in.

With the chosen configuration of the implemented maneuver planner, at the moment when R sends out its first lane change trajectory (t=17.7sec), its planned trajectory has a temporal length of 12sec. The planned point at which the vehicle R first enters the main lane is about 6.5sec at a distance of 120m.

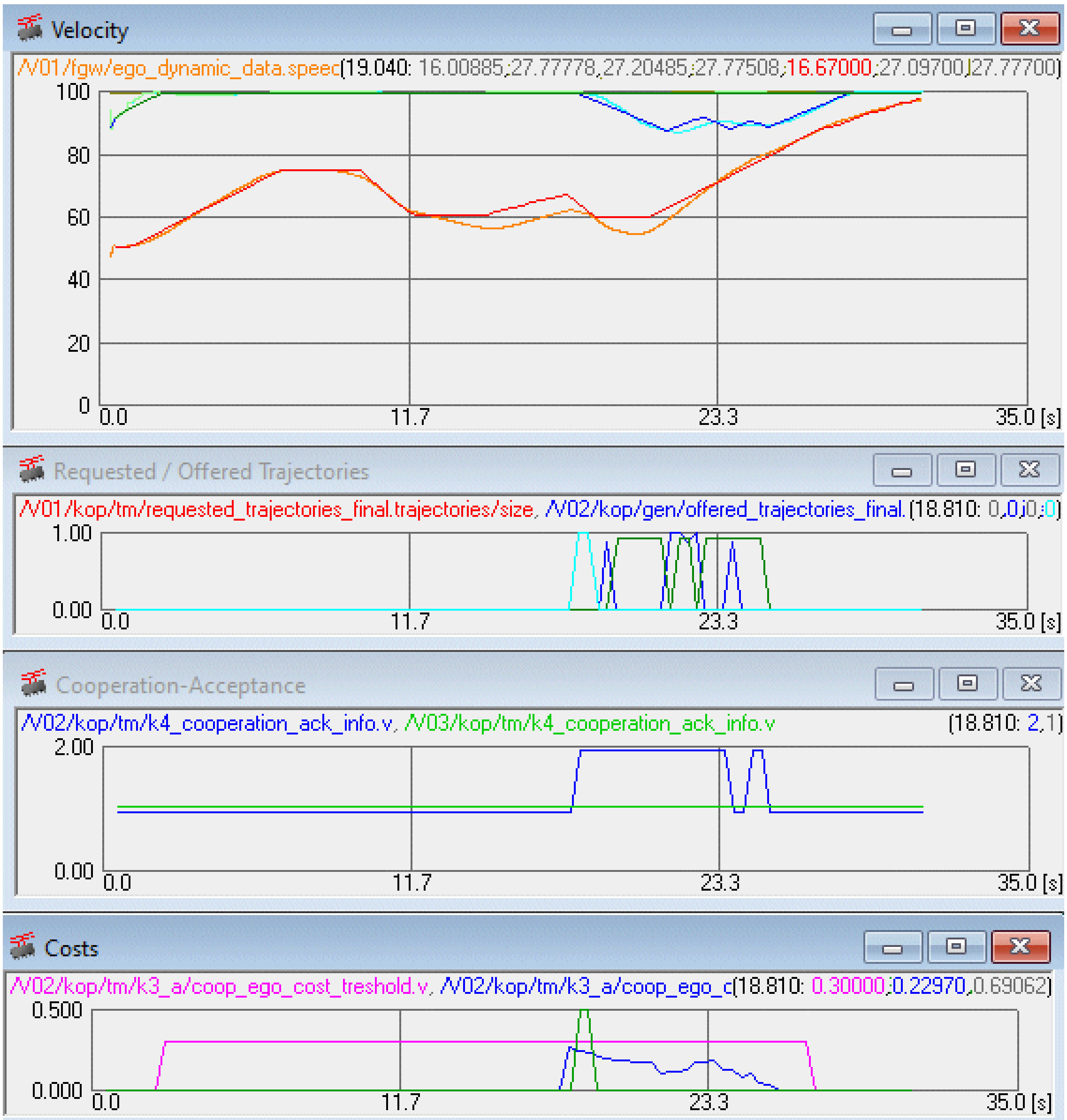


Figure 49: Speed curve "almost forced coooperation" measurement F1_Scenario3_Traffic_Standstill_2021-12-20-06-54_short_forced.bag

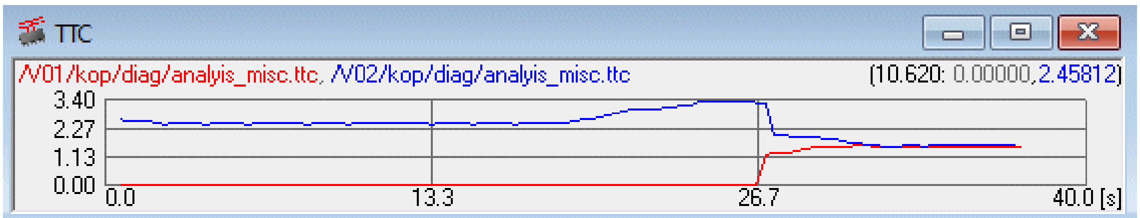


Figure 50: Time-to-collision for the scenario

4.1.8 Forced cooperation / Different understanding of the situation

The reduction of the safety distance by R during threading can go so far that the vehicle B is quasi forced by R to cooperate. Because if the vehicle B on the main lane keeps its normal distance >=2sec, then the threader - if it considers <=1sec at this moment to be sufficiently safe - can thread into the gap between B and O without any problem. The vehicle on the main lane could only prevent it by reducing the distance to the vehicle in front in turn. Since the situation appears to be free of conflict for the vehicle R, it does not send a demand trajectory. Vehicle B recognizes his intention at **an early stage** from the reference trajectory and can/must then react appropriately. This case can also be understood as an example of a different understanding of the situation: R and B agree on the right-of-way rules, but not on further rules, such as the vehicle distances that are perceived as safe in the situation.

The effect of such a situation can be seen in the next picture. Here the configuration has been changed so that B has a (very large) target TTC of 3.5sec, while R only has to meet one of 1.3sec. One can see in the diagram (t=17.9sec) that B's cost exceeds the threshold at R's implicit "request". Consequently, B does not enter into a cooperation and maintains its speed.

Since R also sticks to his plan based on his own assessment, B has no other option from t=25.3sec (more precisely: the maneuver planner does not find any other collision-free solutions.) than to brake and allow R to follow the desired trajectory. This is communicated to R via the adjustment of the reference trajectory. This represents forced cooperation for B, since B has no other alternative. From R's point of view it is an unnecessary cooperation.

The advantage of the concept here is that the continuously exchanged reference trajectories mean that the intention of the others is known at all times in all the vehicles involved. Thus, the situation can ultimately be resolved without extreme or even dangerous driving maneuvers - even though the vehicles had a different understanding or interpretation of the initial situation.

Extreme examples, such as a different understanding of right-of-way rules (intersection with right-before-left understanding vs. right-of-way-yacht understanding) could unfortunately not be simulated with the existing implementation, but should benefit from the concept in the same way.

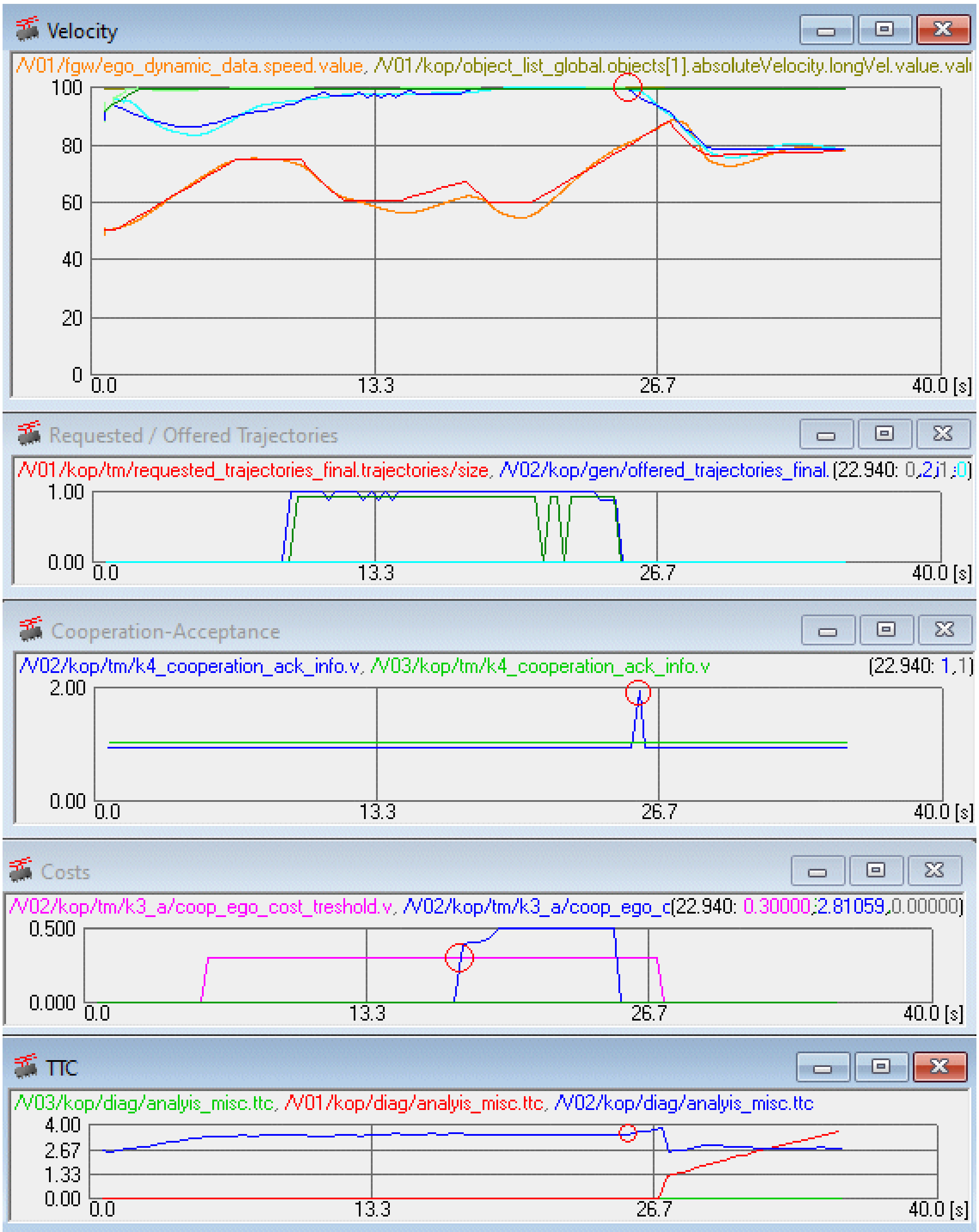


Figure 51: Messung "erzwungene Koooperation" F1_Scenario3_Traffic_Standstill_2021-12-21-17-19-27_forced.bag

4.1.9 Areas of cooperation for selected scenarios

In a cooperation, one partner creates free maneuvering space for another partner requesting cooperation. In many cases, the only way to do this is to temporarily reduce the speed of the partner's own vehicle. The realistic possibilities for the vehicle granting cooperation are limited if the costs incurred are to remain manageable. Using the left-turn scenario as an example, we will show what this means in the current implementation of the maneuver planner with the current configuration.

The CarMaker scenario F5_Scenario1 was used. It consists of a turning vehicle R and a cooperating vehicle B (named V02 in the simulation) coming from the left. The speed was 70 km/h on the main lane and 60km/h for the left-turning vehicle. For simplicity, only the starting position of B was varied. The results are transferable mutatis mutandis. It was evaluated whether active cooperation took place. This means that B actively delayed to allow R to perform his maneuver. If B did not delay, it either denied R its maneuver or B was de facto unaffected by it. The cooperative coordination between the vehicles took place for B about 20sec before reaching the intersection.

It was found that when the starting position of B was varied in the range of 480m to 520m, active cooperation occurred. This corresponds to the equivalent of 2.1sec at 70kmh. This means that B was willing to create a maximum of 2.1sec of additional maneuvering space for R during the 20sec. Thereby the speed of B decreased during the 20sec down to 60kmh.

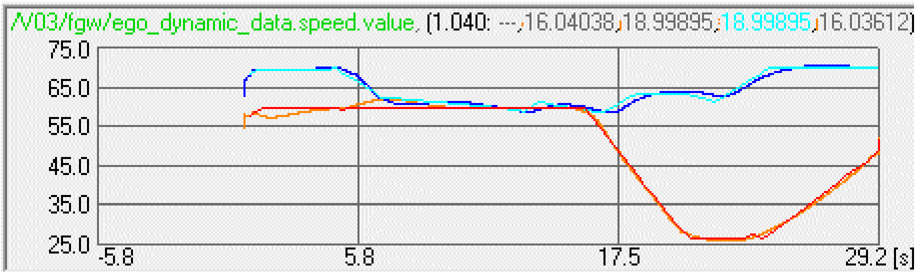


Figure 52: Speed profile at maximum accepted cost for the grantor with crossing traffic.

The same was repeated for scenario F5_Scenario2, in which the vehicle B granting cooperation comes from the right, i.e. both vehicles subsequently travel in the same direction. The speed of the vehicles was equalized to eliminate the influence of the onward travel. The trajectory of R was so long that its acceleration phase behind the intersection was included.

This resulted in a range of B's start position for active cooperation of 555m to 600m. This corresponds to a time interval for a possible cooperation of 2.7sec. The speed of B also decreases here by a maximum of 10kmh.

The two examples show that the area in which two concrete vehicles can work together cooperatively is not very large. Thus, tangible advantages of cooperative maneuver planning can be seen more in the area of full roads.

Furthermore, it can be seen that the possibilities to help someone by a voluntary cooperation are not very large. Despite tuning 20sec ahead of the actual conflict zone, a vehicle with the configuration chosen in the example can create just 2sec or 10% additional maneuver space. In practice, it will probably be even less, since the most energy-efficient way to voluntarily decelerate one's own vehicle is to let it coast (applies to internal combustion vehicles). Here, lower decelerations are achievable than those configured in the implementation used (1.2m/s2).

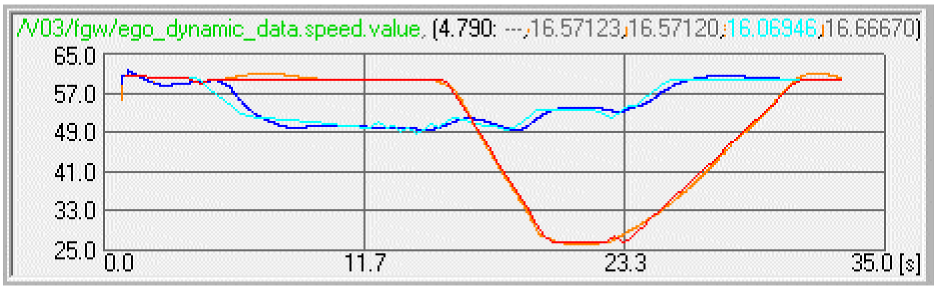


Figure 53: Speed curve at maximum accepted cost for the grantor with traffic in the same direction

4.1.10 Impact / benefit of cooperation for the overall system of all vehicles

Reference should be made here to the work of the project partner OPEL, which is presented in a later chapter. The cooperation concepts are similar enough in this respect so that the results are transferable.

4.1.11 Challenge: Simultaneous cooperation of many vehicles

Unfortunately, this case could not be evaluated with the given resources. Due to limited resources, the implementation of the maneuver planner was designed to allow one vehicle to cooperate. In the case of several vehicles requiring similar cooperation in a dependent situation at the same time, other conditions arise. If, for example, in order to allow one vehicle to merge onto the highway, 2sec of additional maneuver space would need to be created, then with two merge vehicles in succession it would already be 4sec. As explained in the previous chapter, this is not feasible with the currently available implementation, which is designed for comfortable cooperation. In real road traffic, stronger speed delays with shortened distances would be accepted here (preliminary stage of the zipper principle). A new situation arises that was not foreseen in the implementation.

In addition, the architecture of the implemented maneuver planner contains an exponential dependency of the required resources on the number of foreign objects considered, so that no more than 3-4 relevant objects could be included at the same time. Optimization measures could no longer be implemented within the scope of the project. Therefore, the experimental analysis must be left to further research due to the mutual influence of cooperations running in parallel.

The use of alternative trajectories proved to be a valuable optimization measure. Instead of making a consideration for every other foreign vehicle about its situation and resulting possible concessions, the received alternative trajectories were often used. This saved computational resources and effort. Typically, a single alternative trajectory was provided by vehicles willing to cooperate.

4.2 Concept verification Bosch

Bosch is pursuing the cooperative concept designated IMAGinE 2018, which was largely developed and specified by Continental and Bosch. In parallel to the implementation carried out by GUA1 with the further developments made by Continental (IMAGinE implementation), Bosch has also carried out its own implementation for function F1 (cooperative automated threading), which is based on a newly designed graph-based planner. For testing and verification, both implementations were put into operation in the simulation environment as well as Bosch test vehicles. The testing and verification of the cooperation concept for F1 and F5 (cooperative automated turning) was performed together with the partners using the IMAGinE implementation. Since the associated concept verification has already been described in detail by Continental, only reference to it is made here. The concept verification for Bosch's own implementation is described below.

Evaluation metrics for maneuver reconciliation

The following evaluation metrics were defined to quantify the success of maneuver reconciliation:

- Reference trajectory ratio - This metric indicates the ratio of the sampling time points in a simulation run in which a reference trajectory could be calculated to the total number of sampling time points in the simulation run.
- Request trajectory ratio - This metric indicates the ratio of the sampling time points in a simulation run in which a demand trajectory could be calculated to the total number of sampling time points in the simulation run.
- Reference trajectory cost - This metric tracks the cost of the calculated reference trajectories during a simulation run.
- Request trajectory cost - This metric tracks the cost of calculated demand trajectories during a simulation run.

The metric "Reference trajectory ratio" provides an indication of the quality of the developed planner and its real-time capability. If this value is not 1.0, it is possible that reference trajectories are not always calculated, either because the planner does not always work in the scenarios considered or because the calculations take longer than a sampling interval. We can hide the latter aspect in Simulation by reducing the simulation speed. Also, when evaluating the metric, we have to take into account that the Planner has a burn-in phase after the start of the simulation and thus Reference trajectory ratio can be < 1.0 if this is ignored.

The Request trajectory ratio metric provides an indication of whether and how long the coordination of a collaboration takes place. For the metric to be meaningful, it must be interpreted in accordance with simulated scenarios: If a scenario exists in which no cooperation is required, "Request trajectory ratio" must remain zero. In a scenario where cooperation is required, "Request trajectory ratio" must be correspondingly greater than zero. In addition, it is helpful to consider a moving average within a simulation run in order to be able to say when and how long cooperation is negotiated in the simulation. Such a differentiation is helpful when setting the planner and tuning parameters.

The two metrics "Reference trajectory cost" and "Request trajectory cost" are primarily used to support the setting of parameters in maneuver planning and coordination. In addition, they show the advantage of successful cooperation in terms of the sum of the costs of the reference trajectories of the vehicles involved.

In addition to the metrics described so far, we track in how many simulation runs, relative to the total number of all simulation runs, there is a collision between the simulated vehicles. We do not explicitly report this metric below because no collisions occur in the current state of development, regardless of whether cooperation occurs or not.

Preliminary results of the evaluation in simulation

In the following, some results of the evaluation of the F1 function in simulation are presented. The simulation environment used for this purpose consists of a dynamic coupling of the vehicle dynamics simulation *CarMaker* to the Bosch software stack. To be able to interpret the results of the simulations correctly, a visualization tool was developed. This tool allows the graphical representation (see figure below) of the simulated vehicles, the map, the collision-free trajectories (lines) calculated by each vehicle, the selected reference trajectories (crosses) and demand trajectories (circles), and their costs. As a result, a video is generated where the temporal evolution of the vehicles and the trajectories is shown.

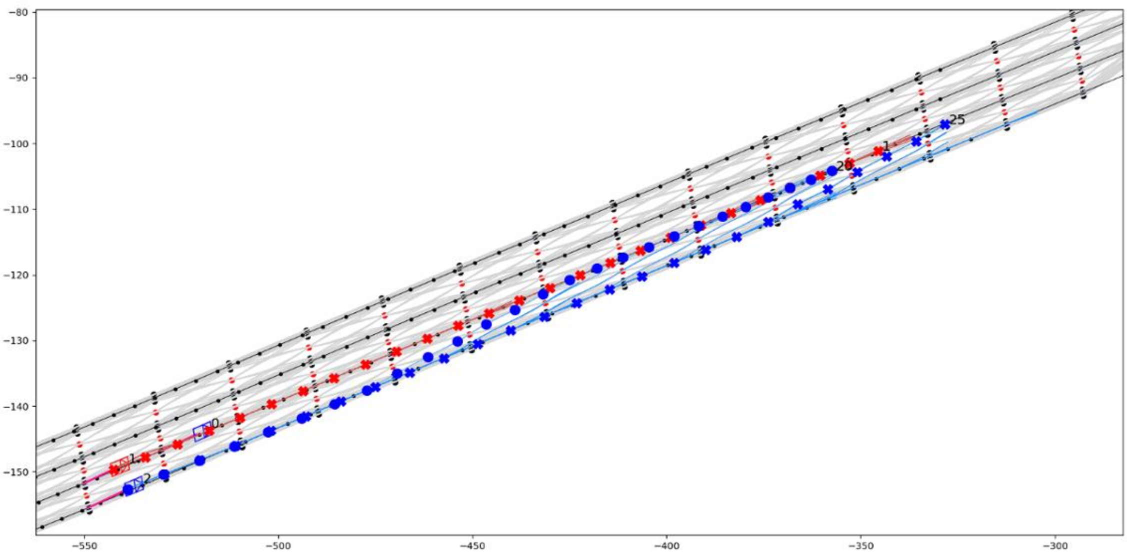


Figure 54: Visualization of the calculated collision-free trajectories (lines), the selected reference trajectories (crosses) and demand trajectories (circles) and their costs.

In addition, we have implemented proprietary assessment tooling that allows, among other things, grid search for parameters in maneuver planning and tuning. This tool allows the evaluation of maneuver tuning using the above metrics when individual parameters are varied. As an example, the following parameters were examined:

- Traj_duration: duration of the calculated trajectories
- Velocity_step: size of the target velocity steps in which trajectories are sampled
- Maximum_cost_request_trajectories: cost threshold above which a demand trajectory is dispatched in the MCM (relative to the cost of the reference trajectory).

In the following, the metrics reference trajectory ratio and request trajectory ratio are shown for the vehicle Vhcl01 (threader) as a function of velocity_step (from 2 to 8 m/s). The reference trajectory ratio remains over 99% independent of the velocity step, indicating that the reference trajectory is calculated correctly in all cases. In contrast, the request trajectory ratio metric varies between 0 and 10% depending on the velocity step. This indicates that the parameter values 4 to 6 m/s provide faster agreement in maneuver tuning. These are therefore to be preferred in maneuver planning.

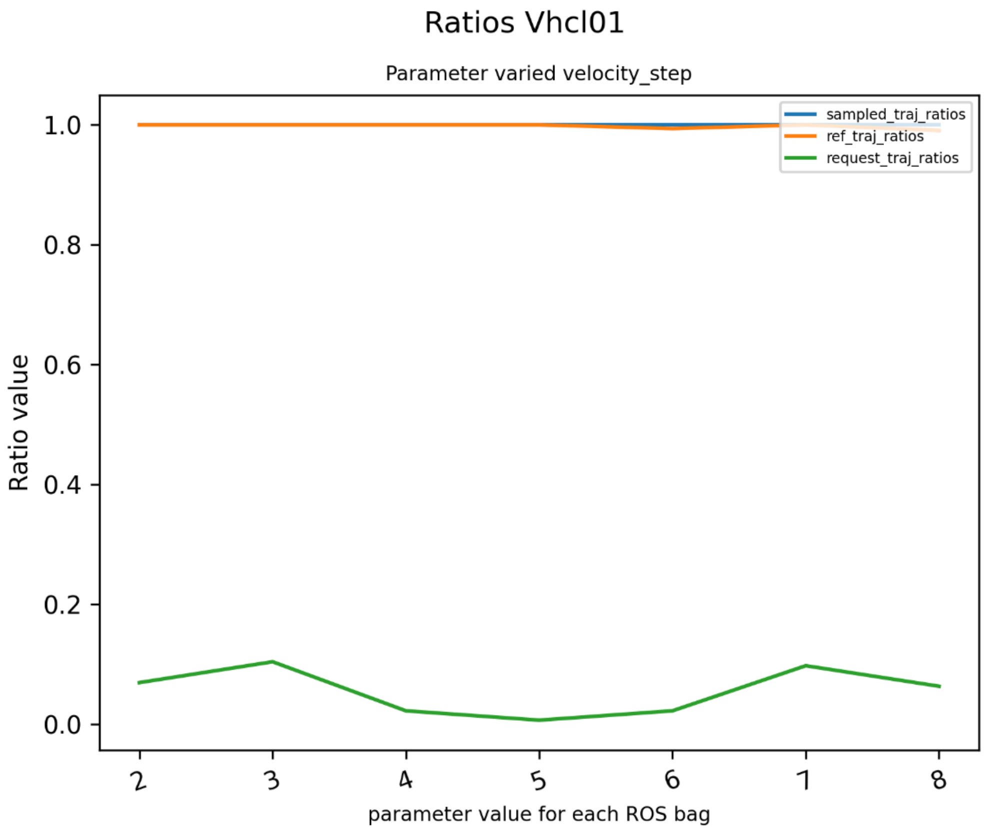


Figure 55: Reference trajectory ratio and request trajectory ratio as a function of velocity_step

The next figure shows the average costs of the reference and demand trajectories from the threader depending on the trajectory duration (from 4 to 14 seconds). It can be clearly seen that longer reference trajectories have higher costs, since the threader has to stay on the acceleration lane as long as the vehicles on the main lane have not agreed to cooperate. The costs of the demand trajectories, on the other hand, remain relatively constant as they switch to the main lane (see figure above).

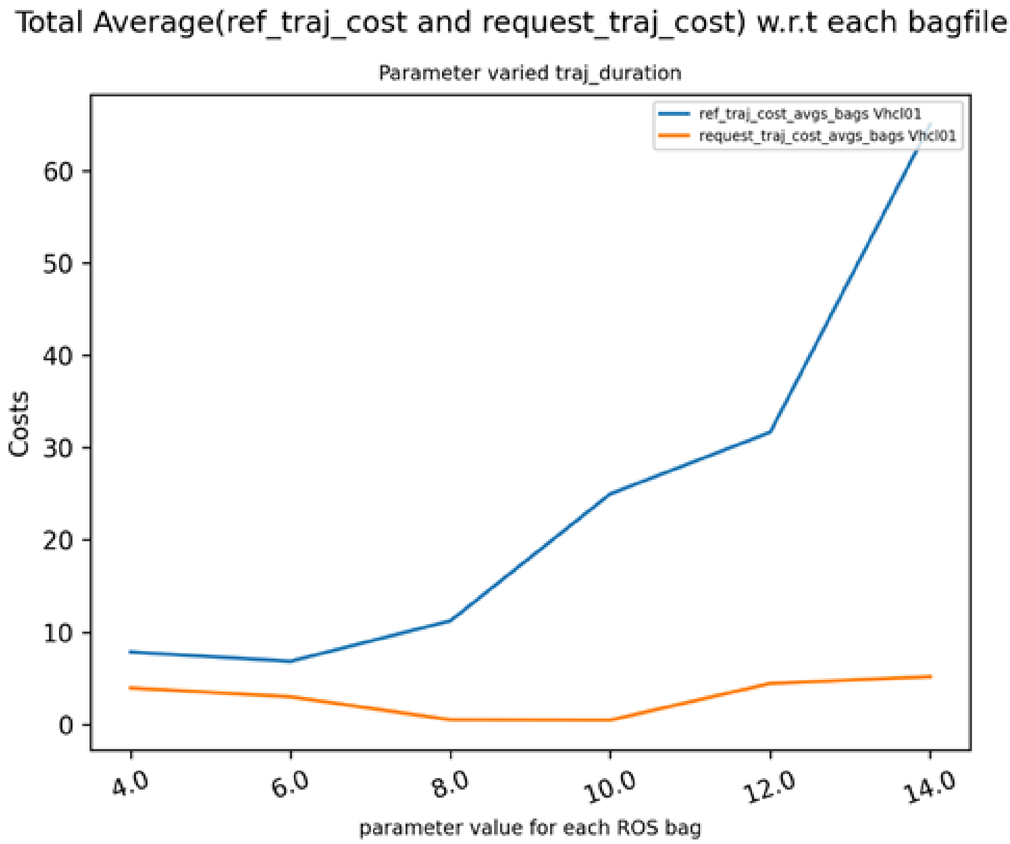


Figure 56: Average cost of reference and demand trajectories as a function of trajectory duration.

Then, the costs of the reference and demand trajectories for both vehicles (Vhcl00: cooperating vehicle on the main lane, Vhcl01: threader) are presented over time. The simulation was repeated for different values of the maximum_cost_request_trajectories parameter (from 0.7 to 0.95). While for some parameter values the trajectory costs remain consistently low (i.e., the vehicles travel their desired trajectories), for other values the cost of the cooperating vehicle's reference trajectory increases sharply at times, indicating that it had to brake too hard.

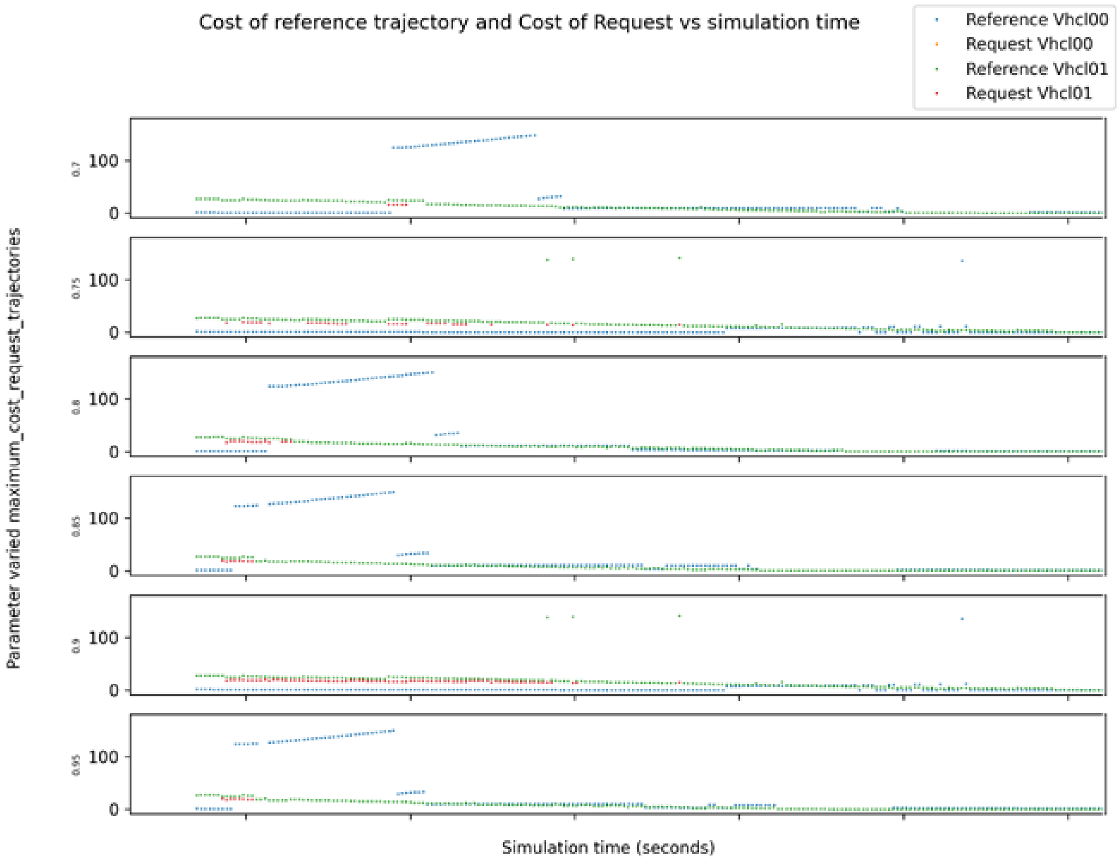


Figure 57: Costs of reference and demand trajectories over time as a function of the demand trajectory selection threshold.

Based on these results, the parameterization of the "maneuver planning and coordination" module was optimized to increase the probability of success of the cooperation. In addition, these simulation results are validated by measurements with test vehicles on the test track.

4.3 Concept verification Volkswagen

4.3.1 Verification Function F1 and Cooperative Maneuver Planner

The following describes how the partner-specific cooperative maneuver planner was verified using IMAGinE function F1 ("cooperative threading"). As part of the verification, it should be checked whether the system is executable according to the functionality specified in Deliverable D2.5. For this purpose, a cooperative threading scenario (F1) should be simulated with three different parameter sets. This is to verify whether the expected cooperative behavior can be observed. It is also to be verified whether the temporal course of the exchanged MCMs corresponds to expectations.

To verify the system, a threading situation with the two cooperatively equipped vehicles V01 and V02 was considered, which is shown in Figure 58. The situation is designed in such a way that both vehicles have the same target speed, so that V01 reaches the merge lane next to V02.

Thus, in order to merge onto the highway, V01 must slow down or cooperate with V02. Table 2 gives an overview of the three parameter sets of the cooperative maneuver planner as well as the expected behavior of V01 and V02.

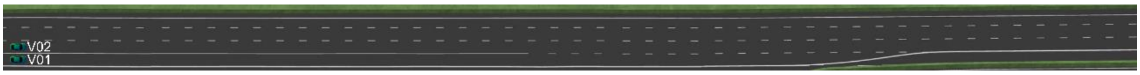


Figure 58: Threading situation used for verification with cooperative-equipped vehicles V01 and V02. To vary the cost of braking in the threading lane, V01 starts slightly ahead or behind V02, depending on the scenario.

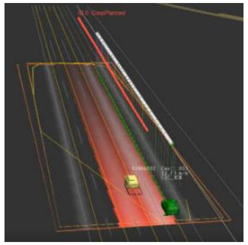
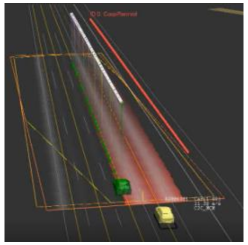
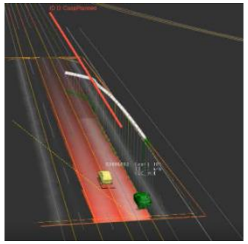
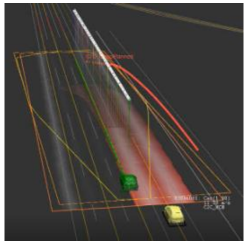
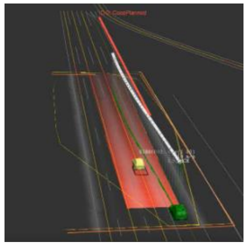
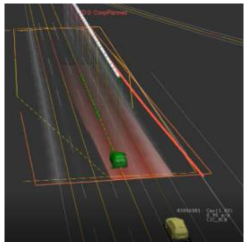
Table 2: Three sets of parameters used to verify the cooperative maneuver planner and the expected behavior of V01 and V02.

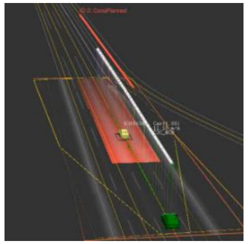
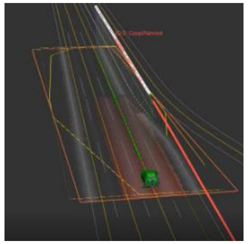
Parameter set	V01 MinCR	V02 MaxCI	Expected behavior V01	Expected behavior V02
1	high	(irrelevant)	• due to the parameterization with a high value for the MinCR, the cost difference of the interim trajectories I-AK and I-NK does not exceed the MinCR • therefore V01 does not express any wishes in this pass • thus V01 must brake and enter the highway behind V02	• since V02 does not receive any requests, V02 maintains its plan trajectory and does not perform a lane change
2	low	low	• due to the parameterization with a low value for the MinCR, the difference of the interim trajectories I-AK and I-NK exceeds the MinCR as soon as a lane change is possible • therefore V01 expresses wishes in this passage • since V02 continuously rejects these requests, V01 has to slow down and enter the highway behind V02	• V02 receives desire trajectories from V01 • due to the parameterization with a low value for the MaxCI, the difference of the interim trajectories I-AK and I-PK exceeds the MaxCI • therefore V02 continuously rejects the incoming requests, maintains its plan trajectory and does not perform a lane change
3	low	high	• due to the low parameterization of the MinCR value, the difference of the interim trajectories I-AK and I-NK exceeds the MinCR as soon as a lane change is possible • therefore V01 expresses wishes in this passage • Since V02 accepts the threading request, V01 can merge onto the highway next to V02 without braking	• V02 receives desire trajectories from V01 • due to the low parameterization of the MinCR value, the difference of the interim trajectories I-AK and I-PK falls below the MaxCI • thus V02 accepts the incoming request, makes the I-AK its new plan trajectory and performs a lane change to the left lane

Observed behavior with parameter set 1:

As part of the verification of the system, videos were recorded from the planner view of V01 and V02 respectively. Individual frames of these videos are shown in table 3. The table also describes the observed behavior of V01 and V02. The behavior corresponds to the expectations of parameter set 1 according to table 2.

Table 3: ADTF views of the planners of V01 and V02 during a run with parameter set 1. The green vehicle in each case represents the ego vehicle of the respective planner instance. The z-coordinate of the trajectories is a measure for the velocity.

Simulation time (s)	ADTF Planner View V01	ADTF Planner View V02	Observed behavior V01 & V02
4 s			• Both V01 and V02 generate a plan trajectory (white in this case) and send it as an MCM message to the other vehicle. • Both V01 and V02 receive the plan trajectory of the other vehicle (here dark orange) as MCM and display it correctly. • Since at the beginning of the scenario the lane marking of the threading lane has been pulled through, V01 is not yet planning a lane change.
10 s			• As soon as the solid line of the threading lane ends, V01 plans a lane change onto the highway (white trajectory). ○ From the drop in the trajectory, it can be seen that V01 plans to reduce its speed and merge behind V02. ○ V01 does not generate a desire trajectory at this time or at any time thereafter. • V02 receives the new plan trajectory from V01, but does not need to adjust its own plan trajectory because it does not collide with V01's plan.
18 s			• A few seconds later, V01 has already slowed down enough to start changing lanes. • V02 continues to drive and plan in the right lane of the highway.

Simulation time (s)	ADTF Planner View V01	ADTF Planner View V02	Observed behavior V01 & V02
30 s			• A few seconds later, V01 has successfully merged onto the highway behind V02. • V02 continues to drive and plan in the right lane of the highway.

To determine how reproducible the behavior of V01 and V02 is, the scenario was run three times repeatedly with this set of parameters. Figure 59 shows the trajectories of these three runs for V01 and V02 as local coordinates relative to the road. It can be seen that V02 had not changed lanes in any of the runs to allow V01 to merge onto the highway. The trajectories traveled by V01 vary slightly between the runs. However, the variations correspond to the typical variations of the non-deterministic planning characteristics of the Volkswagen maneuver planner. In addition, Figure 60 shows all of V01's desired trajectories as well as all of V02's cooperative responses to desired trajectories. As expected, no desired trajectories were dispatched in V01's three runs.

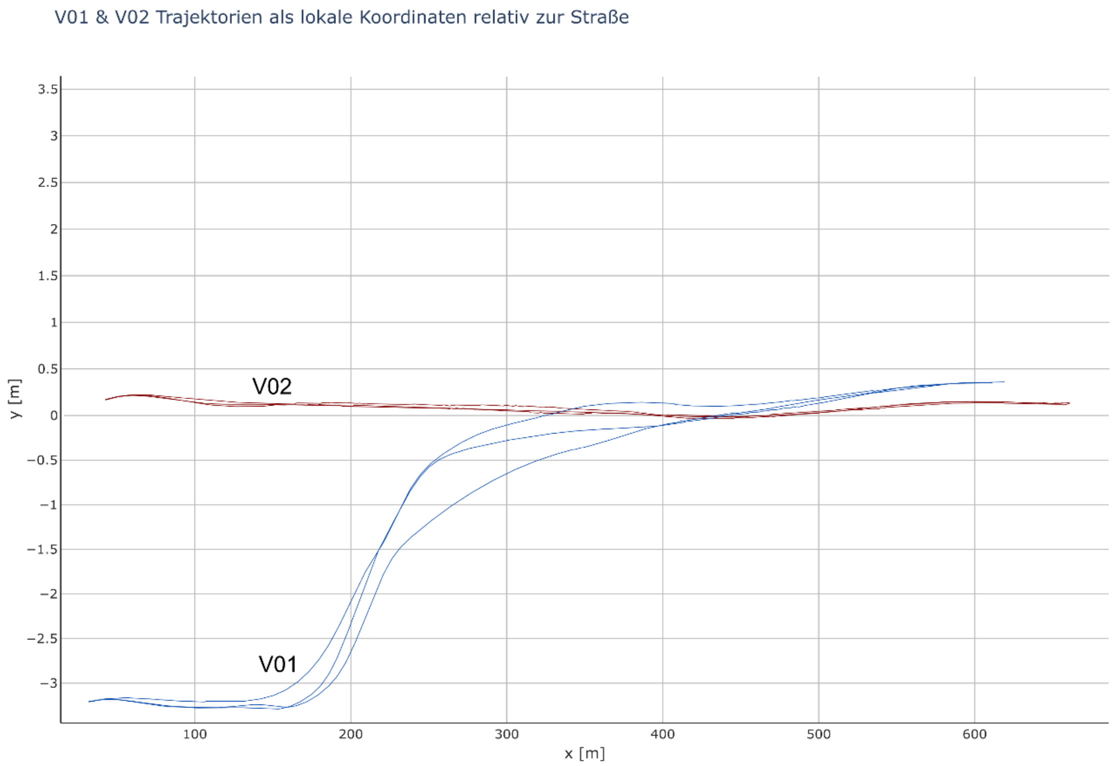


Figure 59: Local coordinates relative to the road of the trajectories of V01 and V02 in three runs with parameter set 1.

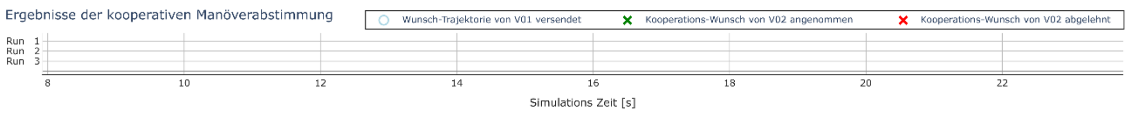
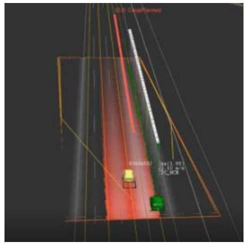
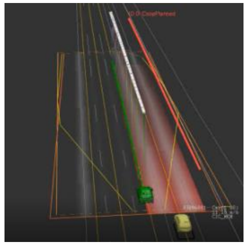
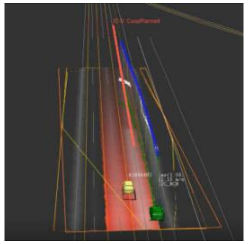
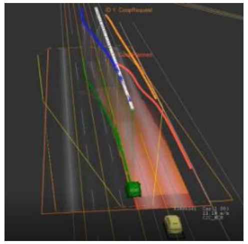


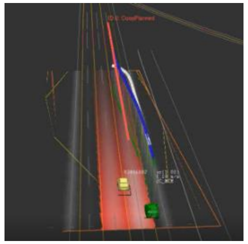
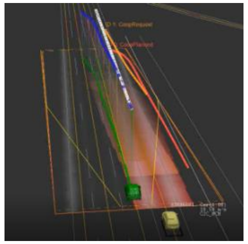
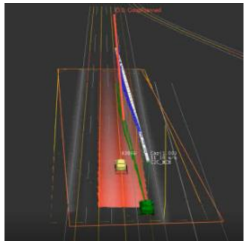
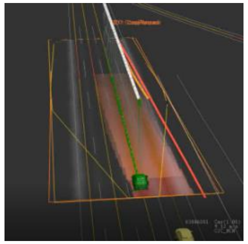
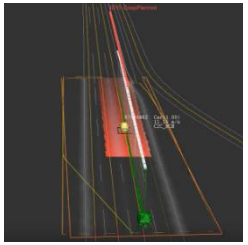
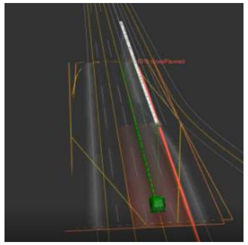
Figure 60: Results of cooperative maneuver tuning between V01 and V02 in three runs with parameter set 1. It can be seen that, as expected, no desired trajectories were sent.

Observed behavior with parameter set 2:

In accordance with the procedure with parameter set 1, videos from the planner view of V01 and V02 were also recorded for parameter set 2. Excerpts from these videos and the observed behavior of V01 and V02 are shown in table 4. Again, the behavior corresponds to the expectations of parameter set 2 according to table 2.

Tabelle 4: ADTF views of the planners of V01 and V02 during a run with parameter set 2. The green vehicle in each case represents the ego vehicle of the respective planner instance.

Simulation time (s)	ADTF Planner View V01	ADTF Planner View V02	Observed behavior V01 & V02
4 s			• Both V01 and V02 generate a plan trajectory (white in this case) and send it as an MCM message to the other vehicle. • Both V01 and V02 receive the plan trajectory of the other vehicle (here dark orange) as MCM and display it correctly. • Since at the beginning of the scenario the lane marking of the threading lane has been pulled through, V01 is not yet planning a lane change.
10 s			• As soon as the solid line of the threading lane ends, V01 plans a lane change onto the highway (white trajectory). ○ From the drop in the trajectory, it can be seen that V01 plans to reduce its speed and merge behind V02. • At this point, V01 additionally generates a desired trajectory that contains a threading while maintaining the current speed (blue trajectory). • The planner view of V02 shows the state of a subsequent planning cycle by receiving the plan (dark orange) and desired (light orange) trajectories of V01 as MCM. • V02 retains as plan trajectory (white) its previous plan and thus (indirectly) rejects V01's request. • The interim trajectory I-AK that V02 used to assess its own incremental costs is shown in V02's planner as an evaluation trajectory (blue) (but not sent as an MCM).

Simulation time (s)	ADTF Planner View V01	ADTF Planner View V02	Observed behavior V01 & V02
12 s			• V01 therefore retains deceleration on the threading lane as plan trajectories (white) in the subsequent planning cycles. • Continuously, V01 continues to generate desire trajectories (blue) that represent threading onto the highway while maintaining the current speed at any given time. • V02 continuously continues to evaluate V01's desire trajectories, but continues to reject them due to the low parameterization of the MaxCI. • Accordingly, V02 continues to maintain travel on the right lane of the highway as the plan trajectory (white) and represents the I-AK used as the evaluation trajectory (blue).
15 s			• A few seconds later, V01 has slowed down enough to begin threading onto the high-way behind V02. • Furthermore, however, V01 generates a desired trajectory (blue), which still repre-sents a more favorable threading onto the highway compared to the planned trajec-tory (white), and sends it as MCM. • V02 also rejects these requests and maintains its plan trajectory (white).
30 s			• A few seconds later, V01 has successfully merged onto the highway behind V02. • The most favorable interim trajectory now no longer collides with the plan trajec-tory of V02, so V01 now no longer generates desire trajectories. • V02 continues to drive and plan in the right lane of the highway.

Also with this parameter set, the scenario was run three times repeatedly. Figure 61 shows the trajectories of these three runs for V01 and V02 as local coordinates relative to the road. Analogous to the runs with parameter set 1, it can be seen that V02 had not changed lanes in any of the runs to make room for V01 to thread. Again, slight discrepancies can be seen between the trajectories of V01 and V02, which can be attributed to the non-deterministic planning of the Volkswagen maneuver planner. In addition, Figure 62 shows all wish trajectories from V01 as well as all cooperative responses to wish trajectories on the part of V02. It can be seen that V01 continuously sends wish trajectories as MCMs in all three runs starting around 10 s (simulation time). Likewise, it can be seen that these wishes are continuously rejected by V02. Thus, the results of this cooperative maneuver tuning are also in line with the expectations for parameter set 2 from table 2.

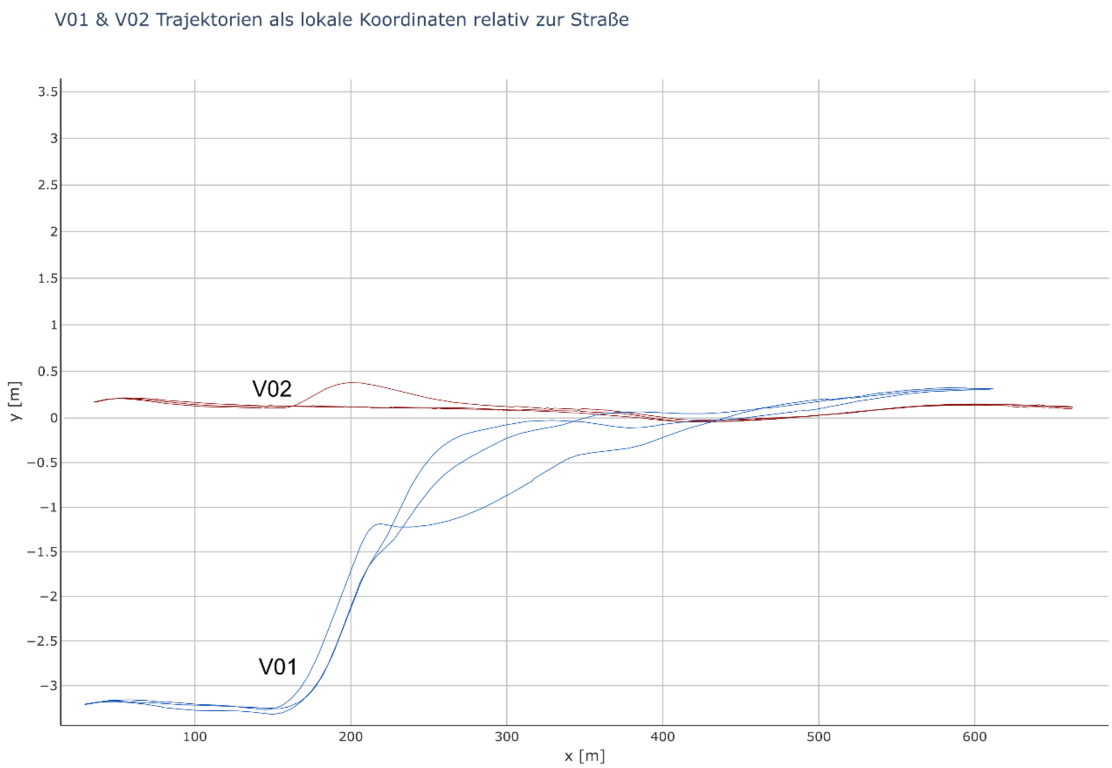


Figure 61: Local coordinates relative to the road of the trajectories of V01 and V02 in three runs with parameter set 2.

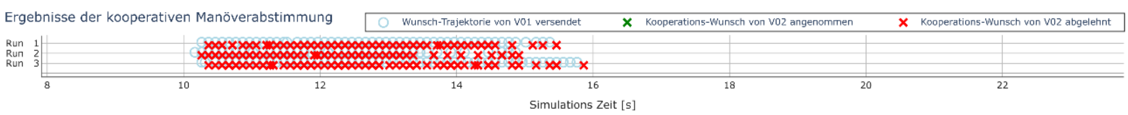
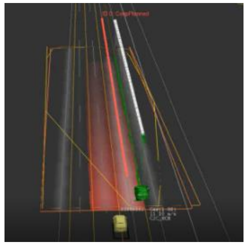
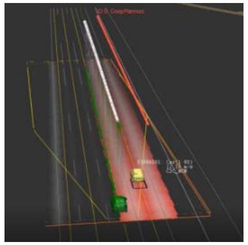
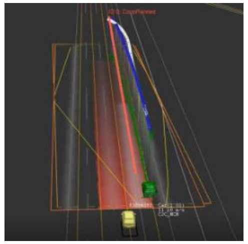
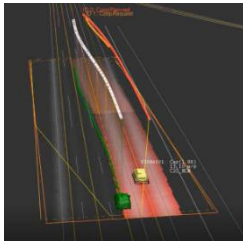


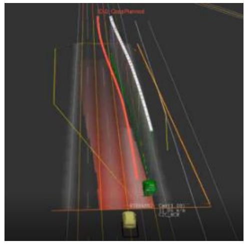
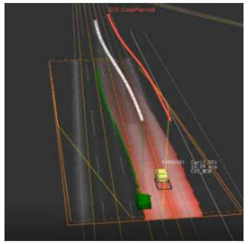
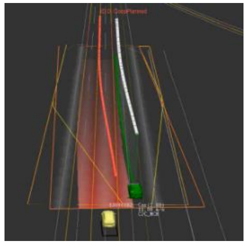
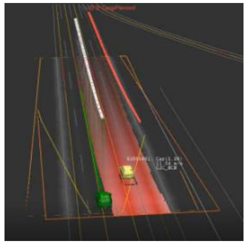
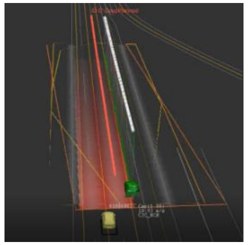
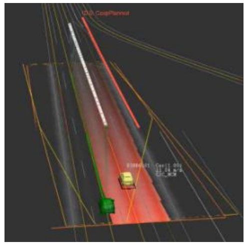
Figure 62: Results of cooperative maneuver tuning between V01 and V02 in three runs with parameter set 2.

Observed behavior with parameter set 3:

Videos from the planner view of V01 and V02 were also recorded for parameter set 3. Table 5 shows excerpts of these videos as well as the observed behavior of V01 and V02. As with the previous parameter sets, the observed behavior matches expectations according to table 2.

Tabelle 5: ADTF views of the planners of V01 and V02 during a run with parameter set 3. The green vehicle in each case represents the ego vehicle of the respective planner instance.

Simulation time (s)	ADTF Planner View V01	ADTF Planner View V02	Observed behavior V01 & V02
4 s			• V01 and V02 generate a plan trajectory (white) and send it as an MCM message to the other vehicle. • V01 and V02 receive the plan trajectory of the other vehicle as MCM (here dark orange) and display it correctly. • Since at the beginning of the scenario the lane marking of the threading lane has been pulled through, V01 is not yet planning a lane change.
10 s			• As soon as the solid line of the threading lane ends, V01 plans a lane change onto the highway (white trajectory). ○ The temporary drop in the trajectory indicates that V01 is planning to reduce its speed in order to merge behind V02. • Since a reduction in speed according to the planner's cost parameterization is associated with an increase in cost, V01 additionally generates a desired trajectory at this time that includes threading while maintaining the current speed (blue trajectory). • The planner view of V02 shows the state of a subsequent planning cycle by receiving the plan (dark orange) and desired (light orange) trajectories of V01 as MCM. • V02, due to the high parameterization of the MaxCI, (indirectly) accepts the request by using the I-AK as the new plan trajectory (white), and thus plans a change to the middle lane of the highway.

Simulation time (s)	ADTF Planner View V01	ADTF Planner View V02	Observed behavior V01 & V02
10.2 s			• V01 thus already plans a lane change onto the highway in the following planning cycle while maintaining its speed, since this interim trajectory is now collision-free (I-AK). • Thus, no more cost-effective I-NK interim trajectory exists either, so V01 no longer expresses a desire here or hereafter. • V02 continues to maintain as the plan trajectory (white) the lane change to the center lane of the freeway.
17 s			• A few seconds later, V01 is already almost completely on the highway. • V02 has almost completely moved to the middle lane of the highway in parallel with the threading process of V01. • Desired trajectories are no longer generated here either.
20 s			• In the further course, V01 and V02 travel slightly offset next to each other on the highway.

Analogous to the procedure with the other parameter sets, the scenario was repeated three times. Figure 63 shows the trajectories of these runs for V01 and V02 as local coordinates relative to the road. In contrast to the runs with parameter sets 1 and 2, it can be seen that V02 performed a lane change in each of the runs to allow V01 to merge. In addition, Figure 64 shows V01's desired trajectories and all cooperative responses to these desired trajectories on the part of V02. It can be seen that in all three runs, starting at a time of about 10 s (simulation time), V01 sent two or three desired trajectories as MCMs that V02 accepted. V01 sent more than one wish trajectory here, since the further wish trajectories were already generated before V02 had adapted its plan trajectory to the acceptance of the first wish. In the further course of the simulations, no further wish trajectories were sent. Thus, these results also correspond to the expectations for parameter set 3 from table 2.

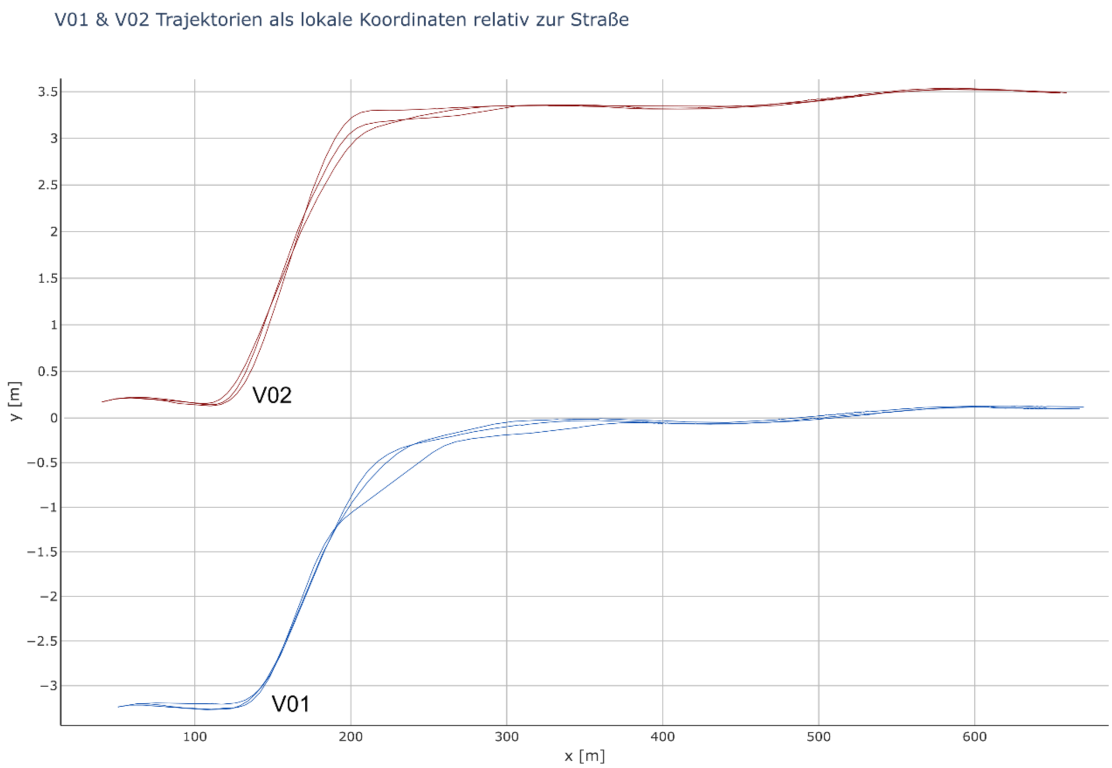


Figure 63: Local coordinates relative to the road of the trajectories of V01 and V02 in three runs with parameter set 3.

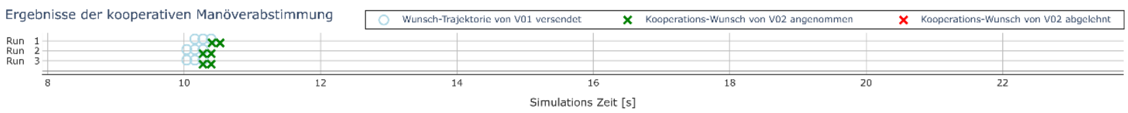


Figure 64: Results of cooperative maneuver tuning between V01 and V02 in three runs with parameter set 3.

Final Evaluation:

In summary, the expected behavior according to the definitions from table 2 could always be shown for all three parameter sets, even with multiple repetitions of the simulation runs. Thus, the verification of the cooperative maneuver planner can be considered successful.

4.3.2 Verification function F3 and cooperative environment model

The function "Cooperative Overtaking on Rural Roads" is based on the concept of Collective Perception. The basic idea is that knowledge about perceived road users is passed on to other road users via V2X communication. What one person cannot perceive himself with the vehicle's own sensor technology, be it due to occlusion or insufficient sensor range, can perhaps be seen by another. The mutual exchange of this knowledge results in an expansion of the existing knowledge in each participating vehicle through the knowledge of others (collective perception). Ideally, each of the involved road users has the same knowledge about the current traffic situation at any given time. In reality, this will probably remain an ideal due to the highly dynamic nature of the traffic situation. Nevertheless, a significant improvement of the environment knowledge can be expected by this knowledge exchange. With this technology, the environment model of the vehicle's own sensor system becomes a "cooperative environment model".

4.3.2.1 Function F3 "Cooperative overtaking on country roads".

Figure 65: How the collective overtaking warning works

The IMAGinE function F3 uses the exchange of so-called Collective Perception Messages (CPM) via V2X to extend the environment knowledge represented by the Cooperative Environment Model developed in IMAGinE. Figure 56 shows the driving scenario on which this function is based: The visibility of a vehicle is restricted by a truck driving ahead, so that an oncoming vehicle cannot be perceived with its own vehicle sensors (Figure 56, left).

The truck in front, however, can perceive the oncoming vehicle by means of its own sensors. It is also equipped with V2X and can thus send information about the oncoming vehicle to the vehicles in the vicinity via CPM (Figure 56, center). The following vehicle receives the CPM and completes its own Cooperative Environment Model with this information. The IMAGinE function F3 interprets the information from the Cooperative Environment Model and warns the driver of oncoming traffic accordingly in the Cooperative HMI (Figure 56, right).

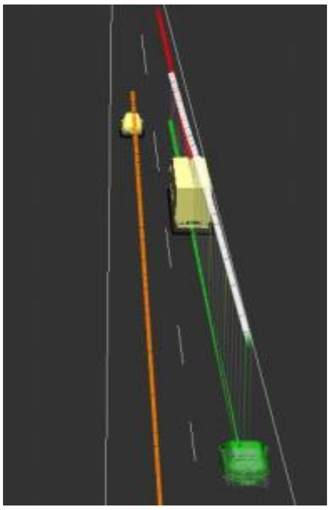


Figure 66: Realization of the F3 function for cooperative overtaking on country roads in the simulator.

Figure 66 shows the implementation of the F3 function in the simulator. In CarMaker, the corresponding szanario is implemented as described in Figure 56. In the CarMaker test automation, the parameters that are necessary for the F3 are set. These include a longer planning horizon, since this must include the complete overtaking process. Also, the cost of a change to the oncoming lane must be balanced with the cost of a reduced speed (in case Ego stays behind the vehicle in front) and the cost of the minimum distance (which may be undercut for a short time during the overtaking).

The parameters from the CarMaker test automation of the IMAGinE environment are passed to the Cooperative Maneuver Planner. The task of the Cooperative Maneuver Planner is to calculate the trajectories for the automated drive including the overtaking maneuver. Cooperation in the sense of exchanging desired and planned trajectories does not take place in this function. The maneuver is performed on the basis of the IMAGinE environment model.

The IMAGinE core technology underlying this function is therefore the Cooperative Environment Model (supplemented by a Cooperative HMI if a driver has to be involved). From the Cooperative Maneuver Planner only the calculation of the plant trajectory is used here; desired trajectories are not needed for this scenario and consequently no Maneuver Coordination Messages (MCM) are sent. Since the warning function is not a core technology of IMAGinE, but requires the Cooperative Environment Model, the validation of IMAGinE function F3 is performed by the validation of the Cooperative Environment Model.

4.3.2.2 Cooperative Environment Model (IMAGinE-GUA2)

The environment model, as implemented within IMAGinE, is limited to basic functionality due to resource constraints (time and money):

- For the prediction of the tracks (i.e. the object list), the constant turn/constant velocity model (also called "Linearized Constant Turn Rate and Acceleration" or CTRA model) is used.
- The prediction for the next measured values is done with an Extended Kalman Filter (EKF). This assumes that input values are at least partially linear.
- Prediction and gating assume that all values of the Kalman state are complete (including steering angle and steering angle rate).
- Map matching, which was developed as part of the environment model, is very rudimentary. The assignment of a track to a lane is based purely on the respective position.
- The input data provided by the partner-specific environment model are elements of an object list, which is generated by partner-specific fusion of the vehicle's own sensor data. These objects are in turn fused with the objects from the received V2X messages.
- The environment model assumes "cleaned" input data. It does not perform any preprocessing of the input data.

The visualization of the environment model shows artifacts, especially in the real world, which give hints about the possibilities and limitations of the Cooperative Environment Model. However, due to the large number of partially non-deterministic and superimposed effects, a detailed analysis is difficult. In the ideal world of the simulation, on the other hand, artificial degradations have to be built in to be able to investigate effects of the real world. This was implemented, for the Volkswagen simulator, within the CarMaker environment by IMAGinE partner IPG and outside of it by Volkswagen within IMAGinE.

4.3.2.2.1 Observed artifacts in the real vehicle

Effects that dominantly occurred in reality were mainly drifting objects and additional objects in the visualization compared to reality. The latter is due to the fact that the Cooperative Environment Model created too many tracks, which in turn was attributed to the fact that the incoming data were not "cleaned". This includes, in particular, data with large deviations from the previously measured data ("unclean" or highly scattered measurement data) and false positives (e.g., due to reflections of radar or lidar signals, which were passed on to the Cooperative Environment Model as objects from the partner-specific environment model). The drifting of objects was mainly attributed to incorrect prediction, for which again the omission of information (e.g. due to temporarily not received V2X messages) or non-linear input signals were seen as the cause. The temporary rotation of objects, which was also observed in real test drives, was attributed to missing or incomplete information from the V2X messages for orientation or orientation change.

In order to reproduce the effects observed in reality, various scenarios were created in CarMaker. The test automation of CarMaker, which was specially developed for IMAGinE by the partner IPG, had to be adapted by Volkswagen to the partner-specific conditions so that the parameters set there were also passed on to the Volkswagen modules in the ADTF framework and implemented.

4.3.2.2.2 Replication of the artifacts and their examination in the simulator

In order to be able to trace the possibilities and limits of the Cooperative Environment Model back to reproducible causes, it was now necessary to reproduce the artifacts perceived in the real world in the simulation. To do this, the input signals in particular had to be artificially degraded. Figure 67 shows a scenario used for this purpose.

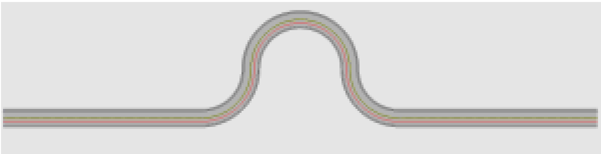


Figure 67: Scenario for the investigation of prediction in cornering.

In the pure study of the Cooperative Environment Model, the map representation was not used. Figure 68 shows the ego-vehicle driving through the road course shown in Figure 67. Another IMAGinE vehicle travels in front of it at a constant longitudinal distance. In this basic scenario, no artificial degradations are used yet. The simulation result is therefore ideal. The longitudinal offset of the CPM objects (orange) is due to the V2X position data updated with lower frequency (compared to the vehicle sensor system) and is therefore correct.

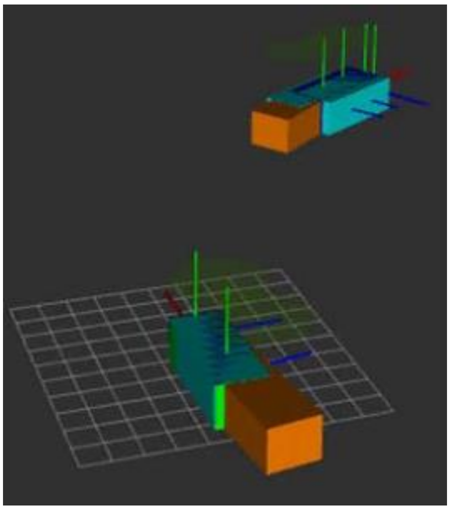


Figure 68: Baseline scenario without interference effects introduced; Ego traverses the curves behind a vehicle in front. The Ego vehicle is shown in green, blue are the object positions detected by the vehicle's own sensors, "orange" are the CPMs and "yellow" (not currently visible in this snapshot) are the CAMs. The results of the object fusions are shown in turquoise.

4.3.2.2.2.1 Constant offset

For CarMaker, the project created the possibility to generate data with constant offset from the ideal sensor data. As expected, this should lead to the fact that, on the one hand, objects perceived with the vehicle's own sensor system have a constant offset. On the other hand, this offset for the perceived objects is also sent with the CPM. However, the determined first-person position remains correct, both in the own perception and for sending via CPM. This could be reproduced in the simulation (see Figure 69).

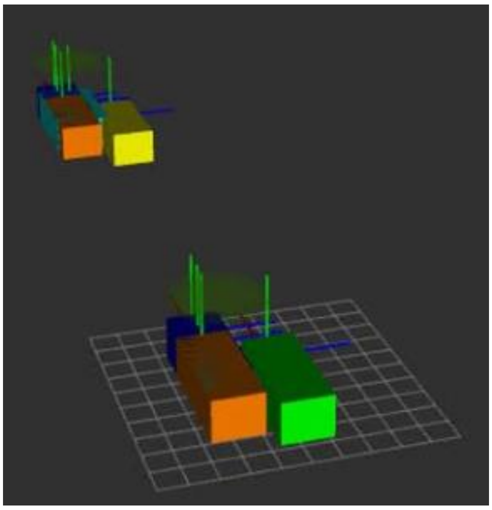


Figure 69: A constant offset in the vehicle's own sensor system leads to an offset (blue) compared to the position transmitted by the vehicle itself (yellow) and the position of the ego vehicle (orange) perceived and communicated by the communication partner (green). The result of the sensor data fusion also shows an offset (turquoise).

The input data of the cooperative environment model are therefore correct with respect to the ego position, as far as the information of the own sensor system is concerned. Via CPM, however, the cooperative environment model receives a constant offset for its own position. Conversely, the other vehicles should have an offset due to their own perception, but receive the correct position via CPM (see Figure 69).

Consequently, filtering the first-person vehicle from the CPM data should not be successful beyond a certain offset and instead a second track with a constant offset should be opened next to the first-person vehicle. This could also be observed (see Figure 70).

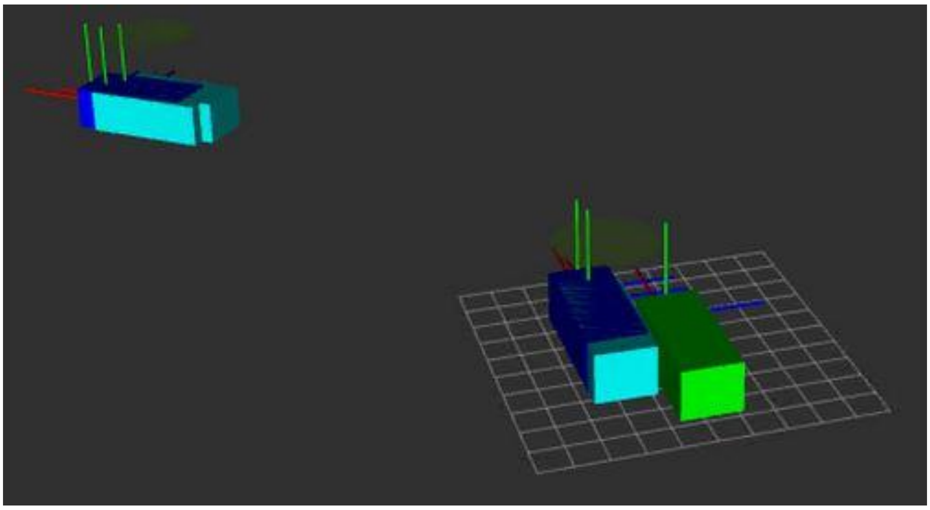


Figure 70: Falsely generated object (turquoise, bottom left) due to received CPM containing an object position that is inconsistent with the first-person position.

4.3.2.2.2.2 Constant offset with superimposed "noise" of the position

The CarMaker environment also allows to "noise" the transmitted first person position. In the simulation, it was possible to simulate that depending on the strength of the selected offset and the superimposed position noise as well as the size of the selected gate for the data fusion process of the cooperative environment model, an additional (and thus incorrect) track was opened (see Figure 71) or not. Therefore, the Cooperative Environment Model behaves correctly in this case as well.

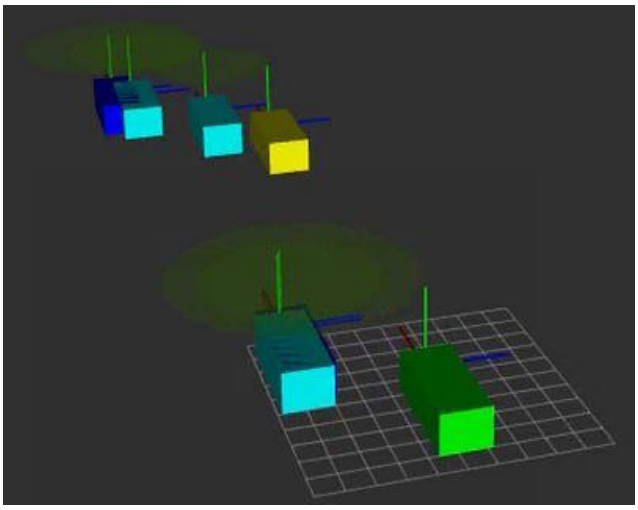


Figure 71: Additionally opened tracks due to too large position errors for the selected gate size.

4.3.2.2.2.3 Lack of information on orientation and change of orientation

Missing information about "yaw rate" and "curvature" should affect the prediction in such a way that the used contant-turn/constant-velocity model leads to wrong predictions of the expected measured values. If the variances are chosen in such a way that the prediction is trusted more than the measured values, a drifting of the object should be observed in curves (see figure 72).

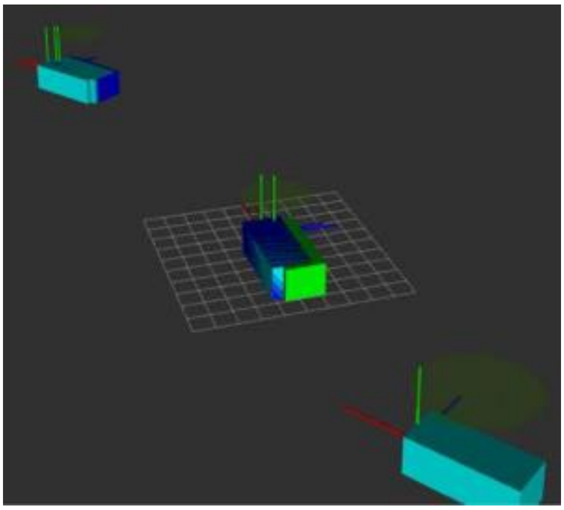


Figure 72: Drifting of an object, here due to a no longer updated track

Likewise, cornering that cannot be traversed with constant steering angle change should cause drifting of the objects with appropriately selected variances. This effect should be more pronounced for curves that cannot be negotiated with a constant steering angle change, always assuming that the prediction is trusted more than the measured values.

The scenarios were run for the investigation of the effect of a constant offset, whereby the offset was varied as a parameter. The evaluation showed that the environment model showed the expected effects as mentioned above only sporadically. In general, no effect was noticeable. This can be explained by the fact that the update rate of the position information is high enough to compensate for the missing information as far as possible.

For the investigation of the influence of non-linear driving on the prediction quality of the Cooperative Environment Model, scenarios with a high proportion of curves were created. This non-linearity represents the first parameter of the investigation. The second parameter varied is speed. Depending on how well the Cooperative Environment Model can handle the influence of these parameters, more or less drift should be seen from the curves.

To investigate the effects of the missing information on "yaw rate" and "curvature", the given scenarios were run again. The varied parameters were the vehicle speeds as the variation of the curve curvature as given by the scenarios. The parameterization of the Kalman-Gain corresponded to the standard IMAGinE values. Isolated drift artifacts were apparent. Apart from that, the data fusion was able to position the two vehicles relatively stable with constant offset (see Figure 73).

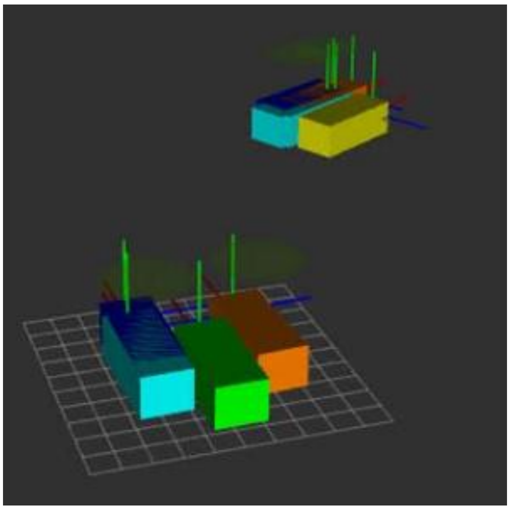


Figure 73: Cornering with constant offset and without yaw rate information; The visualization shows that the offset as an artifact leads to an additional track of the ego vehicle.

4.3.2.2.2.4 Influence of the Kalman-Gain resp. the variances

All of the above parameters affected the data fusion of the Cooperative Environment Model, but did not cause the fusion result to become implausible or show gross errors. Despite artificial degradation, the sensor input data in the simulation is still much more ideal than the data from real vehicle sensors. It is true that a steadiness of the object representations was also less and less given with increasing perturbation. However, smoothing the fusion results in a downstream instance should not result in significant disadvantages for the function development. However, this statement is only valid for a balanced choice of variances of measured values and predicted values.

Therefore, it was now necessary to investigate the influence of the Kalman gain in more detail. For this purpose, the Kalman gain is to be varied in such a way that the prediction is increasingly trusted and the sensor data is distrusted. A Kalman gain is not explicitly named as such in the Cooperative Environment Model. Instead, the operation of the Kalman gain is set by parameterizing the variances in the configuration file. The larger the variance is chosen for a value, the less that value is considered for data fusion. It is expected that with increasing confidence in the predicted data, the fusion will show more pronounced artifacts such as drifts or gyrations.

For this purpose, the variances must be varied in the configuration file of the cooperative environment model in order to better provoke the effects described above. Specifically, these are the parameters cov_modification_default_variance_rel_* for the in-vehicle sensors, cov_modification_default_variance_abs_* for the V2X messages (each with "cov_modification_mode : 3" for "always overwrite") and ekf_process_variance_* for the prediction. The larger the variance is chosen, the greater the fuzziness and the less the consideration for data fusion.

Since the prediction result is trusted more when there are high variances in vehicle sensors and V2X messages, it would have been expected that the prediction would lead to worse fusion results due to the simple models (EKF and CTRA). In the figure below, the effect of the offset is more evident than in the previous figure. This is amplified by the fact that in addition to the constant offset, there is also another distributed offset. In the end, however, no effect clearly attributable to the high variances can be identified.

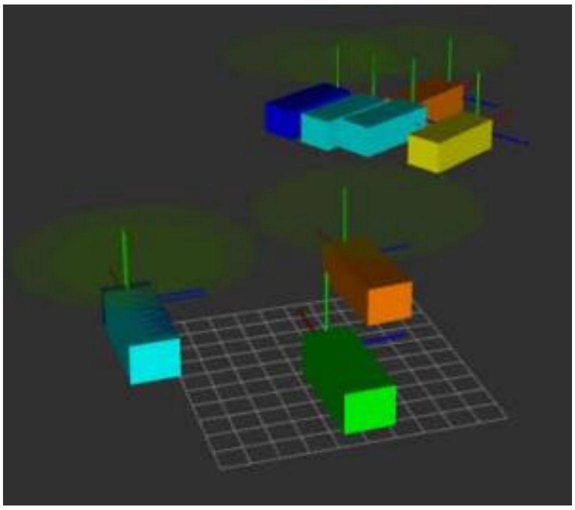


Figure 74: Cornering with high constant offset and high dispersion of position and high variance on the in-vehicle sensor system.

4.3.2.2.2.5 Scalability of the concept

Another aspect to be investigated is the scalability of the environment model. This is because, in view of the effects described above, restrictions arise with regard to the vehicle density to be depicted. The larger the interference effects are, the lower the vehicle density around the ego-vehicle has to be in order for an association of the perceived signals to the tracks managed in the environment model to still make sense. For this study, an intersection scenario was chosen (see Figure 75).

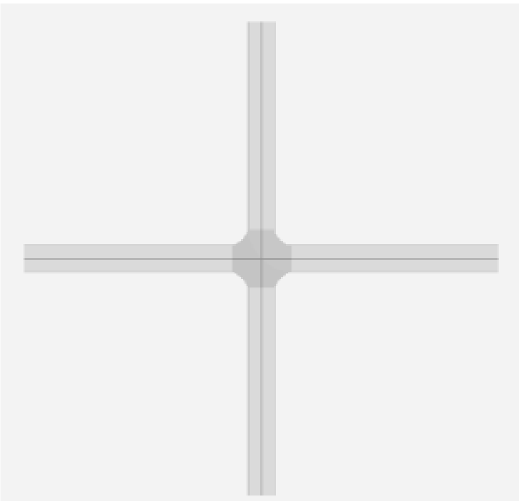


Figure 75: Scenario for the scalability study

Figure 76 shows the basic scenario of the intersection passage without artificially introduced disturbances. It can be seen that an association of the position information can be clearly assigned to each other.

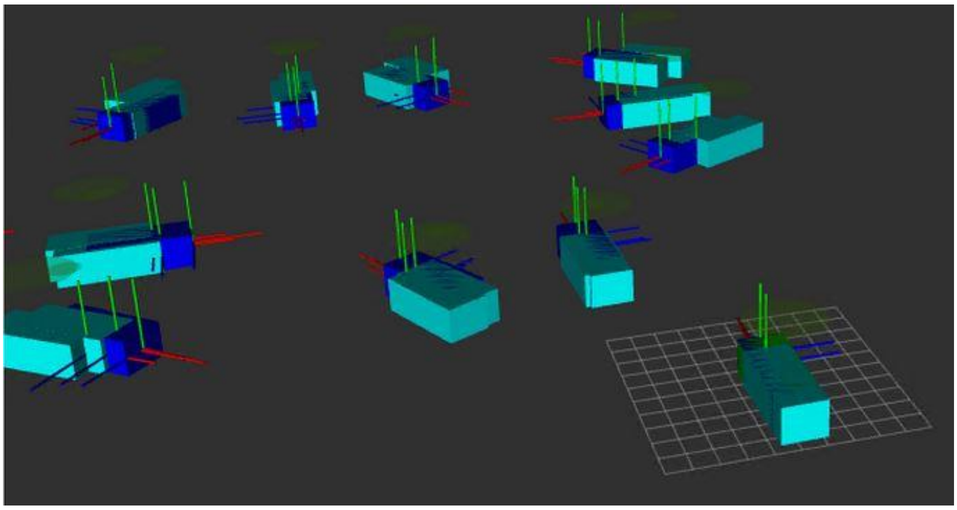


Figure 76: Scalability baseline scenario

Figure 77, however, shows how difficult it is to draw reliable conclusions about the exact number and position of the vehicles actually present when the association uncertainty of the incoming signals is high. Due to the unrealistically low update rate of 1,000 ms for V2X messages in the simulation, association is made unnecessarily difficult, so Figure 77 is actually not useful.

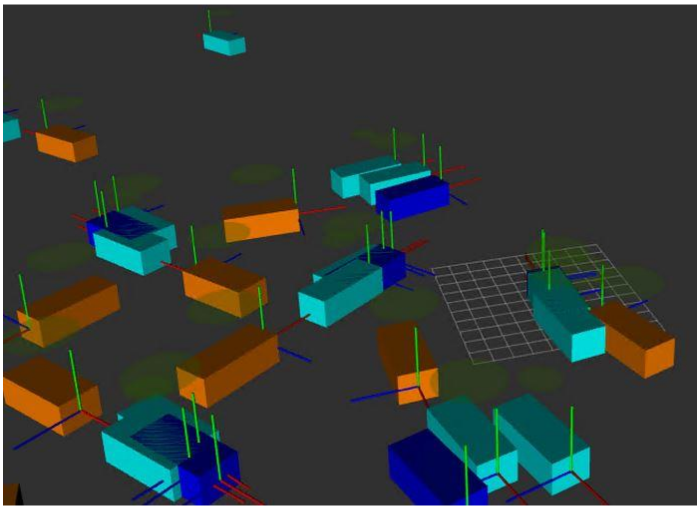


Figure 77: Turning in an intersection with high vehicle density and constantly offset vehicle signals. The assignment to the actual vehicles is still possible because the orange blocks do not deteriorate realistically due to the low update rate of 1,000 ms used in the simulation.

In summary, the Cooperative Environment Model handles data fusion quite stably. A constant offset also has a constant effect on the fusion result. More realistic is certainly the noisy signal, the effects of which can be seen in Figure 74 and which also has the most significant impact on track assignment. The prediction, however, is probably not so bad because the update rate of the measured values is still sufficient, so that EKF and CTRA obviously can cope with it. Consequently, higher variances in the measured values obviously do not have such a strong effect.

4.4 Concept verification OPEL

In this chapter, a simulation-based proof-of-concept of the *Opel Core* concept prototyped within IMAGinE (see concept presentation OPEL (D2.5)) is presented with respect to its fundamental effect on traffic quality based on function F1. The simulation environment used for this purpose, consisting of a static and dynamic coupling of vehicle dynamics simulation *CarMaker* and traffic flow simulation *SUMO*, is described in detail in the scientific publications [1] and [2].

4.4.1 Metrics and scenarios

For the purpose of proof-of-concept of *Opel Core,* to quantitatively evaluate the impact of cooperative maneuver planning and coordination with the concept on various aspects of traffic quality, appropriate evaluation metrics and simulation scenarios are first needed. An overview of the metrics applied here is illustrated in the figure below. Here, these metrics are applied only to the vehicles that are temporarily located in a stationary area, so-called Region of Interest (RoI). This RoI includes a segment of the road where frequent occurrence of cooperative maneuvers is expected (e.g., at the freeway on-ramp). Thus, the following metrics are used in the following, for their mathematical definitions we refer to [1]:

1. Traffic flow
    a. Traffic density *k*
    b. Traffic speed *v*
    c. Traffic volume *q*
2. Coefficient of variation *CV*
3. Time-Exposed Time-to-Collision *TETTC*
4. Spatiotemporal patterns

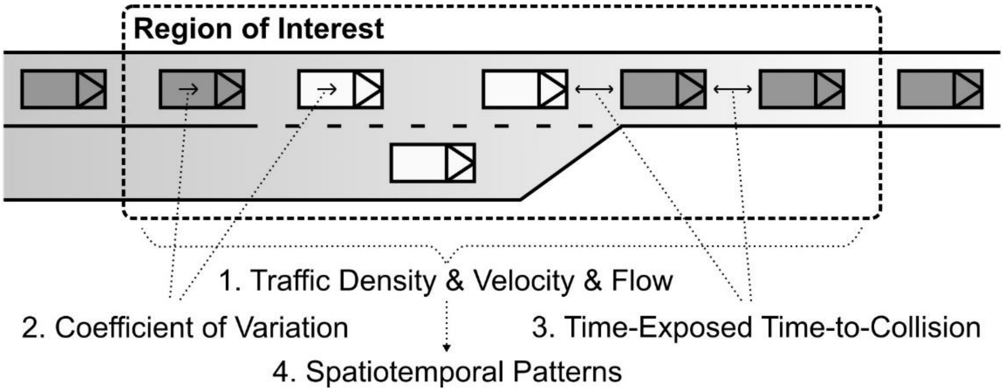


Figure 78: Overview of traffic quality metrics applied to a generic freeway on-ramp (function F1) [1].

In this proof-of-concept, the focus is on three traffic scenarios. These scenarios are generated synthetically with the simulation environment and named as follows depending on the traffic condition they emulate:

1. 'Congested'
2. 'with CMC' (Cooperative Maneuver Coordination)
3. 'Free'

In 'Congested' and 'Free' scenarios, the cooperative maneuver planning and coordination algorithm is disabled, thus creating borderline cases for evaluation. On one side, in the case of the 'Congested' scenario, the merging vehicles always drive to the end of the acceleration lane before starting a non-cooperative merging, generating a significant shock wave each time (worst-case scenario). On the other hand, in the case of the 'Free' scenario, there are no merging vehicles at all, allowing traffic to flow continuously uninterrupted on the highway (best possible scenario). In the case of the 'with CMC' scenario, the algorithm is activated, resulting in multiple cooperative merging maneuvers. Thus, in the case of successful cooperation, the result of the 'with CMC' scenario should be between the results of the 'Congested' and 'Free' scenarios, as expected.

A common configuration of all three traffic simulation scenarios is shown in the table below. Here, in order to achieve the most obvious and clearly interpretable results with the selected metrics, the traffic behavior in the simulation is set to ideal with respect to following trip and speed compliance. Furthermore, perfect V2X communication is assumed, i.e. unlimited range without latencies and losses.

Table 6: Configuration of the simulation scenarios [1]

Parameter	Value
Duration of a traffic scenario	90 s
Number of cooperative maneuvers per traffic scenario	3
Number of lanes on the highway	1
Speed limit on the highway	100 km/h
Traffic demand	7200 Fzg/h
Length of the acceleration lane	250 m
Total length of RoI	500 m

4.4.2 Results

4.4.2.1 Traffic flow

The evaluation results for the traffic flow in the time domain are shown in the following diagrams. There, the traffic density *k,* the traffic speed *v* (including a standard deviation) and the traffic volume *q* over the simulation time *t are* shown for all scenarios 'Congested', 'with CMC' and 'Free'. As can be seen here in the case of the 'Congested' scenario, three non-cooperative merging maneuvers cause noticeable decreases in traffic speed, followed by increases in traffic density, resulting in overall oscillations in traffic volume. In contrast, in the case of the 'Free' scenario, traffic density, speed, and strength always remain constant. At this point, in the 'with CMC' scenario, the positive influence of cooperative maneuver planning and coordination on traffic flow becomes apparent, as cooperation allows for more uniform threading operations, which in turn result in approximately constant (i.e., optimal) traffic density, speed, and strength.

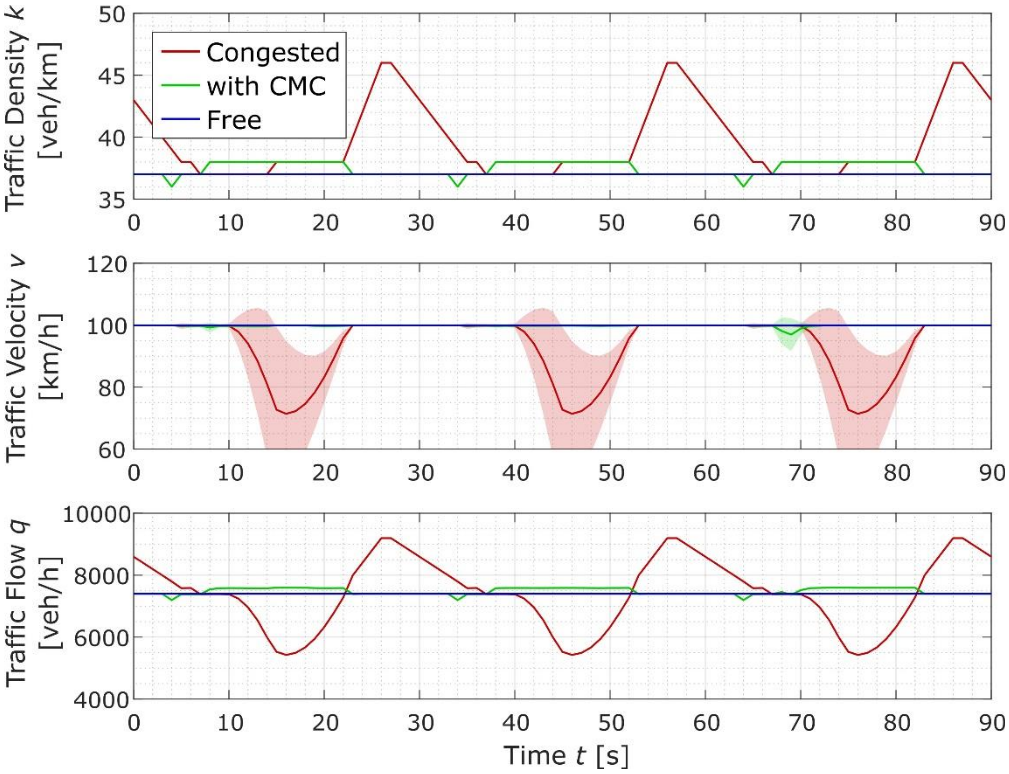
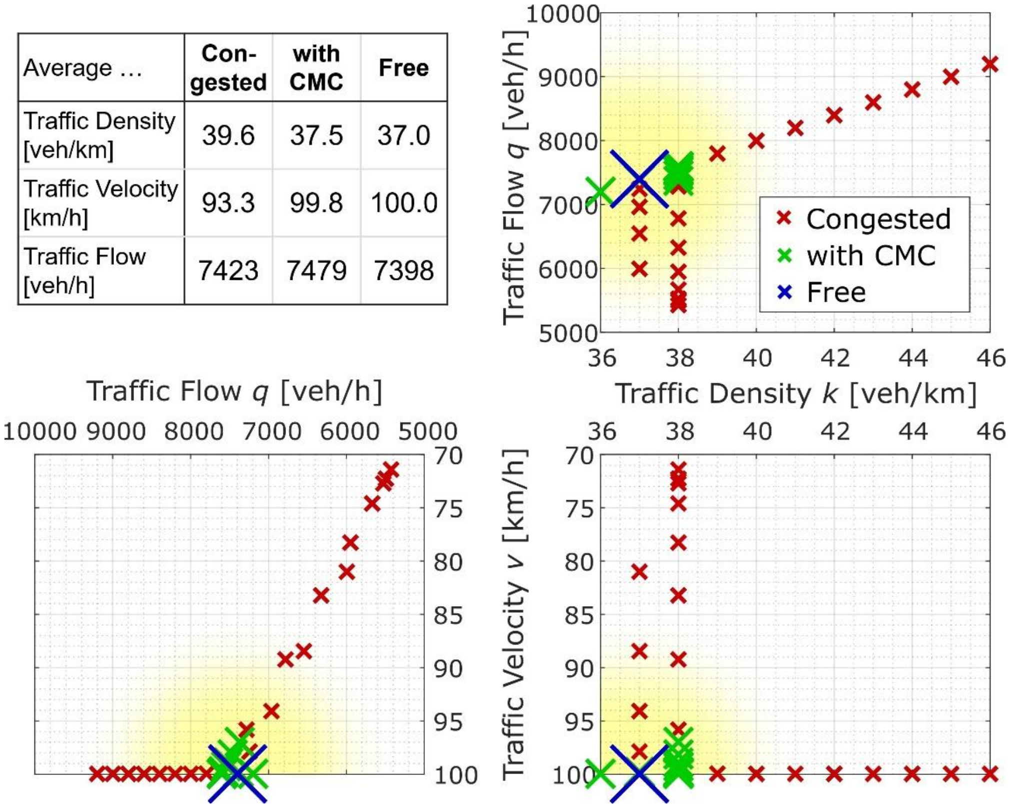


Figure 79: Result - traffic density, speed and intensity in the time domain [1].

Identical simulation results can also be visualized in a so-called fundamental diagram, as shown in the following figure. Here, points in the diagram represent direct relationships between traffic density *k*, traffic speed *v* and traffic volume *q*. Basically, the closer the points are to the border-line case 'Free' (yellow zone), the better is the traffic quality. It can be seen that the points of the 'with CMC' scenario are located close to the 'Free' scenario, whereas the points of the 'Congested' scenario are more dispersed due to the high variations in traffic density, speed and intensity.



Average …	Con-gested	with CMC	Free
Traffic Density [veh/km]	39.6	37.5	37.0
Traffic Velocity [km/h]	93.3	99.8	100.0
Traffic Flow [veh/h]	7423	7479	7398

Figure 80: Result - traffic density, speed and intensity as fundamental diagram [1].

4.4.2.2 Coefficient of variation

In the next step, the coefficient of variation *CV* of the vehicle speeds is evaluated. The average speed and the corresponding standard deviation are determined for each vehicle that is in RoI during the simulation of a traffic scenario. Then the coefficient of variation is calculated from this and displayed in the form of a scatter plot, where each point here represents a vehicle.

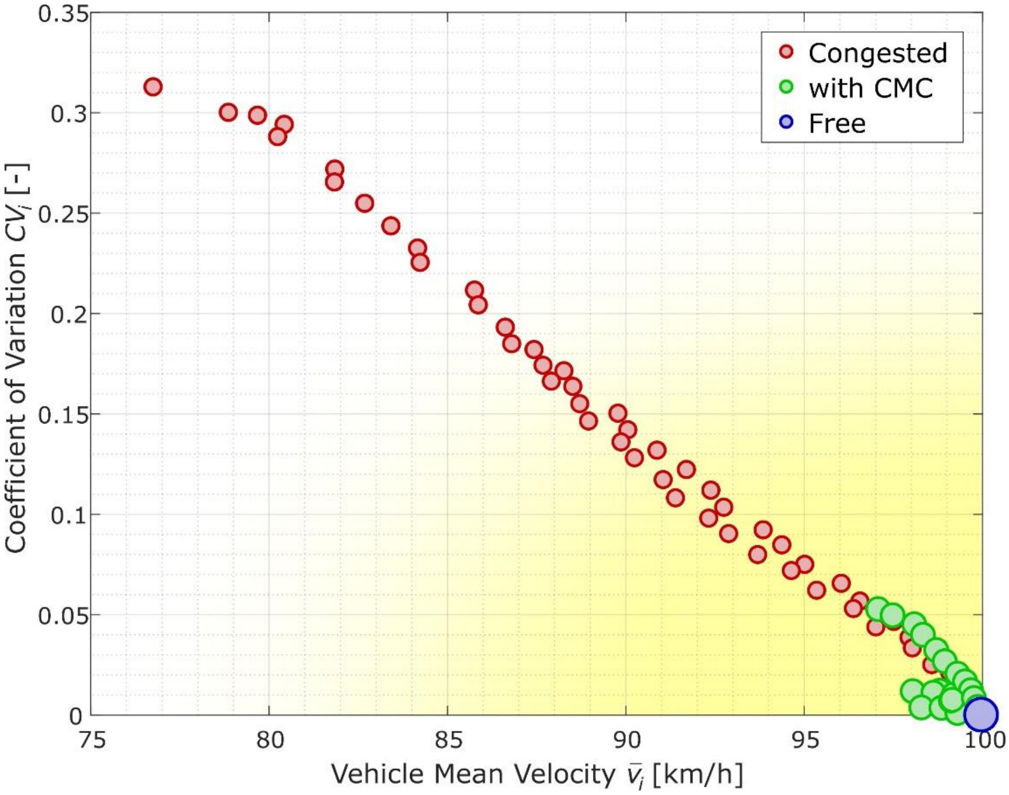


Figure 81: Result - CV over average speed of vehicles [1].

In the case of the 'Free' scenario, all associated points are in one place, which means that all vehicles in the simulation were ideally traveling at 100 km/h without deviations. In the case of the 'Congested' scenario, the points are highly dispersed, indicating lower average speeds and higher speed changes for many vehicles. In comparison, the 'with CMC' scenario demonstrates intermediate values, as the cooperative maneuver planning and tuning algorithm visibly improves the *CV value* by providing more consistent threading at the freeway on-ramp. In general, for better traffic quality, higher speeds with the smallest possible changes are preferred, which is highlighted by yellow zone in the diagram. This results in shorter travel times and better energy efficiency of traffic.

4.4.2.3 Time-Exposed Time-to-Collision

The next metric evaluated in the traffic quality evaluation is *TETTC*, the results of which are shown in the bar chart below. For this purpose, a relatively high threshold value of 25 s was applied, which is due to the ideally assumed driving behavior (subsequent driving model) in the traffic simulation. The number of vehicles with the same (rounded) *TETTC values is* counted through, ignoring *TETTC=0,* and then displayed as a bar.

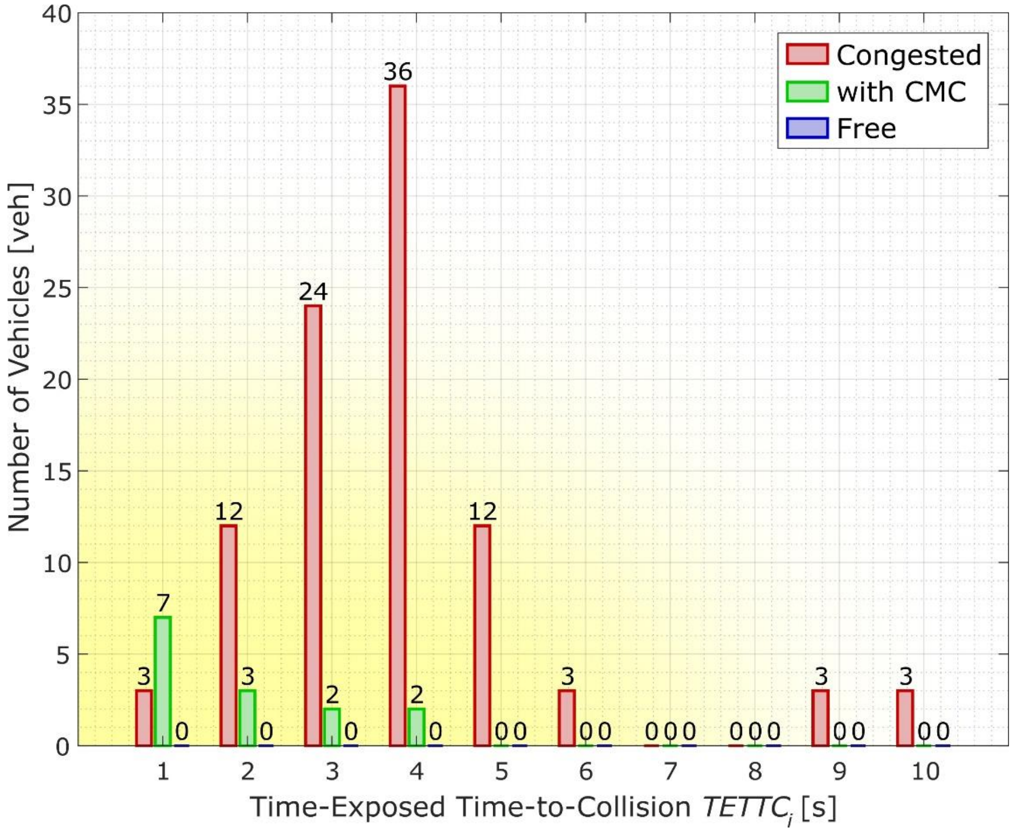


Figure 82: Result - number of vehicles with corresponding TETTC [1].

From the resulting diagram, it can be seen that in the case of the 'Congested' scenario, many vehicles have high *TETTC* due to the reduced distances to the vehicles ahead over longer time periods (several seconds), as they were pushed to do so by the non-cooperative merging maneuvers. In contrast, in the case of the 'Free' scenario, all vehicles have *TETTC=0*. Subsequently, the evaluation of the 'with CMC' scenario provides intermediate values, which is justified by more consistent longitudinal distances between vehicles during the threading events with cooperative maneuver planning and coordination. In general, fewer vehicles with less *TETTC* characterize better traffic quality as well as higher traffic safety, which is represented as the yellow zone in the diagram above.

4.4.2.4 Spatiotemporal patterns

As a final step in the proof-of-concept of *Opel Core, the* spatiotemporal patterns are used, which are shown separately in the following diagrams for each scenario 'Congested', 'with CMC' and 'Free'. Here, the positions *p* of the individual vehicles in RoI are shown as recorded trajectories over the simulation time *t,* as well as the corresponding speeds *v* with different colors. In all diagrams, the beginning of the acceleration lane corresponds to 0 km and the end to 0.25 km. In the case of the 'Free' scenario, the spatiotemporal patterns demonstrate ideal traffic quality in that all vehicles in the simulation had free passage throughout. In the case of the 'Congested' scenario, one can see sharp reductions in speeds caused by three non-cooperative merge maneuvers. These speed reductions resulted in strong shock waves that started at the threading point and propagated upstream, significant that several vehicles had to brake. After the actual threading process was completed and the shock wave dissipated, the traffic flow returned to the free state for a period of time. In the case of the 'with CMC' scenario, the variations in speed are almost imperceptible as the threading vehicles quickly synchronized with the overall traffic flow. The threading itself happened much earlier and caused almost no disturbance to the traffic on the highway. Thus, one can clearly see the positive effect of cooperative maneuver planning and coordination on traffic quality.

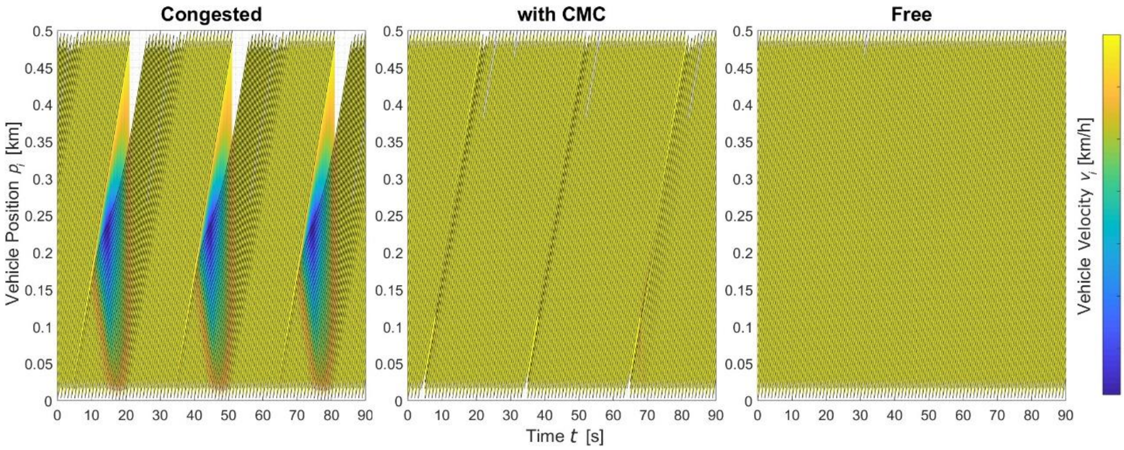


Figure 83: Result - spatiotemporal patterns [1].

4.4.2.4.1 Sources

[1] V. Lizenberg, D. Bischoff, Y. Haridy, U. Eberle, S. Knapp & F. Köster. "Simulation-Based Evaluation of Cooperative Maneuver Coordination and its Impact on Traffic Quality." *SAE International Journal of Advances and Current Practices in Mobility*; vol. 3, no. 6, pp. 3159-3169; Technical Paper 2021-01-0171. 2021; doi: 10.4271/2021-01-0171.

[2] V. Lizenberg, M.R. Alkurdi, U. Eberle & F. Köster. "Intelligent co-simulation framework for cooperative driving functions." *IEEE ICCP: 17th International Conference on Intelligent Computer Communication and Processing*. 2021; Cluj-Napoca, Romania.

4.5 Results Concept Verification (BMW)

4.5.1 Verification GUA1 Concept "IMAGinE 2018

BMW AG's approach and work to verify the GUA1 concept "IMAGinE 2018" are described in their own contributions to Deliverables D3.2 and D4.4. As presented there and in the semi-annual reports, the following results were achieved:

1. The supplied activation of GUA1 function F1 has been successfully revised.
2. Thus, the GUA1 function F1 was simulated in CarMaker in several expressions:

   a. First complete delivery status from February 2021
   b. As final delivered GUA1 software version from 30.4.2021 with several improvements until 13.08.2021
   c. Current GUA1 software version from November 2021, further developed in IMAGinE, with additions, especially from the project partner Continental.

3. The GUA1 function F1 was simulated in the driving simulator software SPIDER with the following results:
   a. First complete delivery status F1 from February 2021: Only visually successful retraction processes could be represented, but functionally without intended cooperation of the subsequent vehicle
   b. Software status 30.4.21: no investigations performed in SPIDER, because of still problems in CarMaker and bad reproducibility due to old synchronization concept
   c. Current IMAGinE GUA1 software version from November 2021 with new synchronization concept: successful integration and simulation of test scenarios at freeway entrances, but so far still without intended cooperation granting
   d. The same test scenario mixed with an entering GUA1 vehicle and with vehicles equipped by Bbasic (see below) on the main carriageway: Bbasic vehicles cooperate as intended on the basis of the MCM messages sent by the GUA1 vehicle.

As a result, software version 2c. was able to show a successful cooperation after cooperation request and granting of cooperation in an adapted scenario with 3 GUA1 vehicles (modified scenario F1, 1st scenario 2nd variant of the specifications, in short F112). This corresponds to the result in point 3, which was also presented by the project partner Continental. General functionality in other scenarios, on the other hand, has not yet been successfully demonstrated.

In summary, the current GUA1 software was successfully integrated in the SPIDER driving simulation software. The GUA1 software can control vehicles there even in simple simulator scenarios and perform retract operations at freeway slip roads. The intended function of F1 with active cooperation support could be demonstrated to the same extent as with CarMaker.

Overall, BMW was thus able to contribute to a partial verification of the GUA1 concept and confirm corresponding results of the project partner Continental. However, a "proof-of-concept" in the originally intended scenario scope was not yet possible for the GUA1 concept "IMAGinE 2018" in the driving simulation until the creation of this deliverable.

Instead, for resource reasons, verification of the Bbasic concept was prioritized until further notice.

4.5.2 Verification Bbasic concept

The verification of the Bbasic concept described technically in D3.2 and implemented at BMW by November 2021 was carried out as planned. Successful cooperations functioning as intended were simulated and recorded both in 3-vehicle test scenarios and in larger scenarios with up to 10 intelligent vehicles capable of cooperating simultaneously.

BMW simulator vehicles can be configured so that they are controlled by a driver model that behaves like a driver. The driver behavior model TRM used for this purpose can be parameterized and acts or reacts with driver-like reaction times. TRM also implements driver-like cooperation behavior based on its own perception-based on-board situation assessment.

The new IMAGinE maneuver coordination via maneuver coordination messages enables a fast exchange of information to which automated vehicles can respond with short reaction times. For this purpose, the TRM driver model in IMAGinE has been extended and adapted.

4.5.2.1 Comparisons in controlled test situations

The BMW simulation makes it possible to compare test situations with and without maneuver tuning or with different tuning procedures and parameterizations. In the following, the cooperative driving of the on-board driver behavior model TRM is therefore presented as a "baseline" and compared to the results of IMAGinE maneuver tuning with Bbasic.

4.5.2.2 Representation and evaluation

To test the function of simulated scenarios, videos were used in which relevant events and planning are displayed. In the following, examples of relevant points in time from these videos are reproduced as screenshots. Furthermore, a large amount of measurement data is recorded in the driving simulation. Following the screenshots, relevant variables are displayed and compared over time.

In order to enable a clear comparison between different simulations, plotscripts were created for IMAGinE that show differently configured simulations of a test scenario over time with different colors. Thus, scenarios without and with IMAGinE are compared in the following plots. "Without IMAGinE" means that vehicles cooperate with each other in a driver-like manner without exchanging MCM messages through the TRM driver behavior model of the driving simulation. "With IMAGinE", means that TRM vehicles additionally exchange MCM messages and consider them for their vehicle control and maneuver cooperation. In this way, changes and gains due to early IMAGinE MCM message exchange can be directly tracked in comparison.

4.5.2.3 Proof-of-concept Bbasic cooperation with three vehicles

The following two pictures show the successful cooperation in a simple 3-vehicle test scenario:

1. Cooperation is requested via a principle trajectory into the adjacent lane
2. Cooperation is quickly confirmed by the following vehicle on the main lane ("Grant")
3. The vehicle on the acceleration lane accelerates and shears in, vehicle on the main lane decelerates slightly at the same time.

4. After threading, the distances are normalized and increase to a typical following distance (e.g. time gap of approx. 1.3 seconds).

Bbasic can send and receive the intention indirectly by transmitting a principle trajectory to the new target lane, but also directly by simply transmitting the relative position of the new target lane. The results are almost the same. Since TRM vehicles consider both options when receiving, they can cooperate with other TRM vehicles as well as with GUA1 vehicles. In the following, a simulation with signaling of the need for cooperation by a "principle trajectory" is shown first:

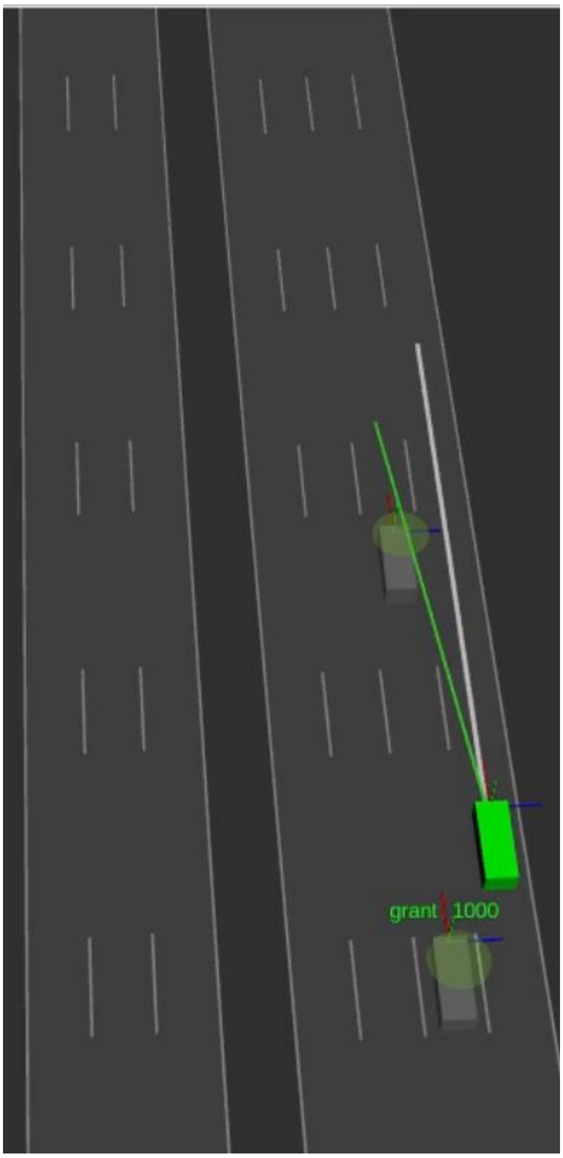


Figure 84: 3s: Cooperation commitment after request with alternating trajectory

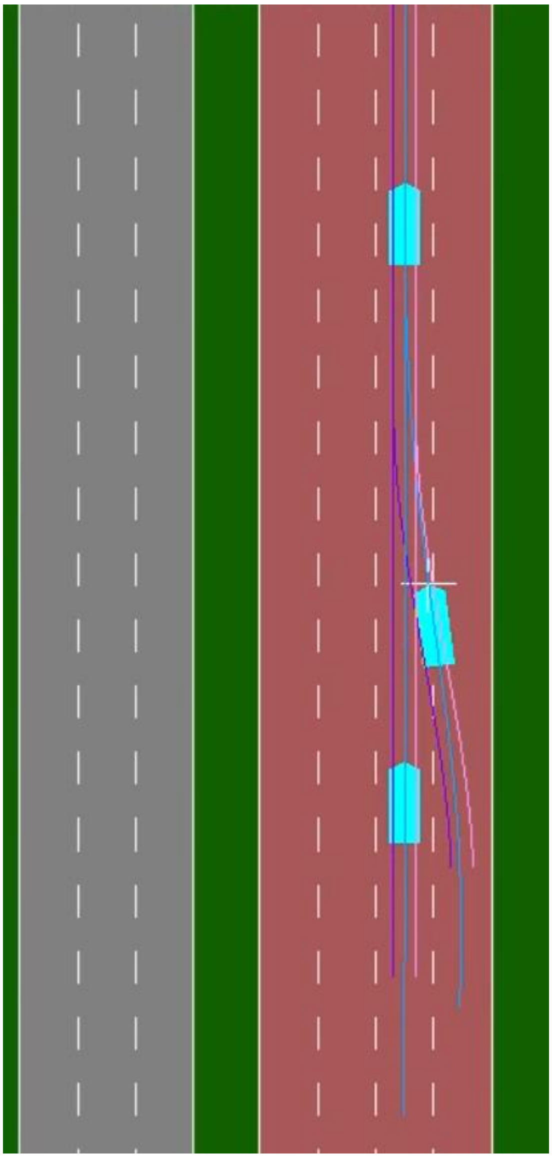


Figure 85: 7s: Reeving after cooperation

In the scenario shown above, the intention is signaled by sending a "principle trajectory" - drawn in green - to the center of the left neighboring lane. Since the selected cooperation partner is addressed explicitly, the principle trajectory does not have to be followed and driven exactly, but it merely signals the need for cooperation. The trajectory actually driven, on the other hand, is traffic-dependent and depends on the optimal distance control to the front and to the rear during the lane change.

In the scenario shown below, on the other hand, the intention is signaled directly by sending a single MCM message attribute "I want to change lanes one lane to the left". The execution of the lane change is again based on the optimal distance control to the front and to the rear during the lane change. As an actually driven ego trajectory, in the same driving situation with the same driving behavior of the surrounding vehicles, this also results in the same trajectory as above, regardless of how the intention is signaled:

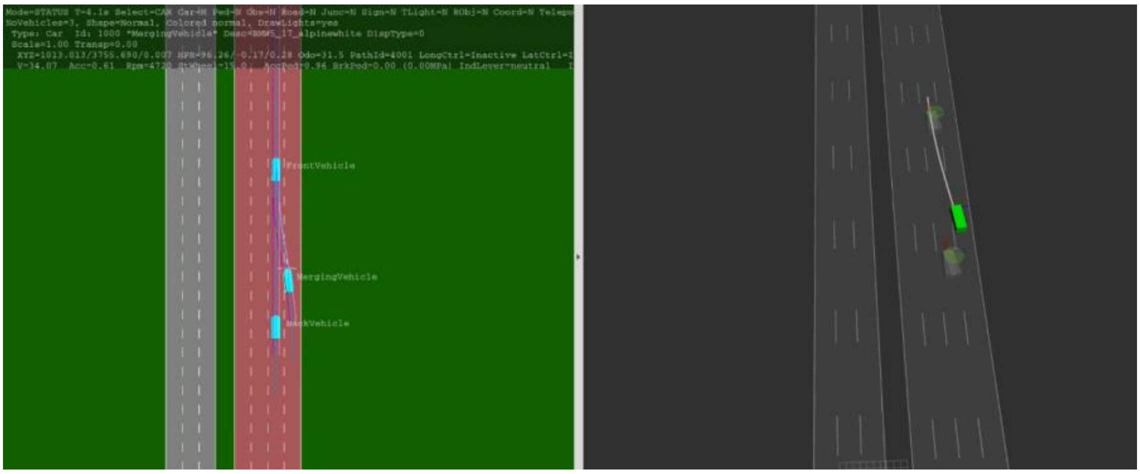


Figure 86: 7s: Reaching in after cooperation on request with intention

As a result, knowledge of the intention is therefore sufficient for the driver to decide for himself/herself on his/her own consent to the desired closing-in procedure on the basis of the actual driving situation and to regulate the advance distance with regard to the relevant criteria - above all driving safety and efficiency aspects - during the closing-in procedure. This regulation can also take into account the driver's own predictions that are deemed sufficiently credible in the actual driving situation. The responsibility for one's own maneuver planning remains in one's own vehicle and is not made dependent on predictions made by other vehicles.

In the following plots, IMAGinE cooperation via the "Bbasic" procedure is compared to the onboard autonomous cooperation behavior of the TRM driving simulator vehicles before, i.e., without exchange and evaluation of IMAGinE maneuver cooperation messages.

4.5.2.4 Time of the cooperative lane change

Due to the early cooperation request via IMAGine MCM, the cooperative lane change in the test scenario can take place about 1 second earlier than a threading process without MCM. Whether a need for cooperation is communicated by trajectory or by intention makes practically no difference to the test scenario:

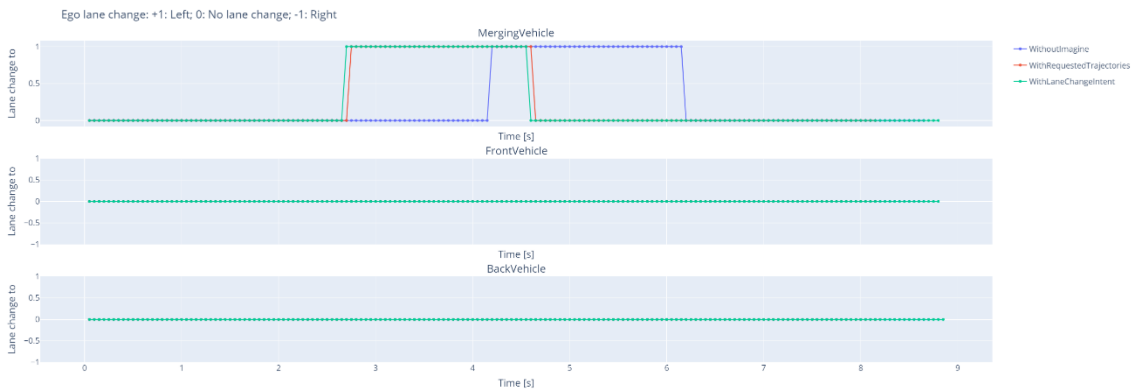


Figure 87: Earlier lane change through IMAGinE cooperation

4.5.2.5 Balanced acceleration profile

Due to the early cooperation, the acceleration profile of the following vehicle on the main lane behind the inbound vehicle is more balanced in the test scenario. Unnecessary acceleration prior to the onboarding process is avoided. Afterwards, the following vehicle can accelerate again sooner behind the accelerating oncoming vehicle:

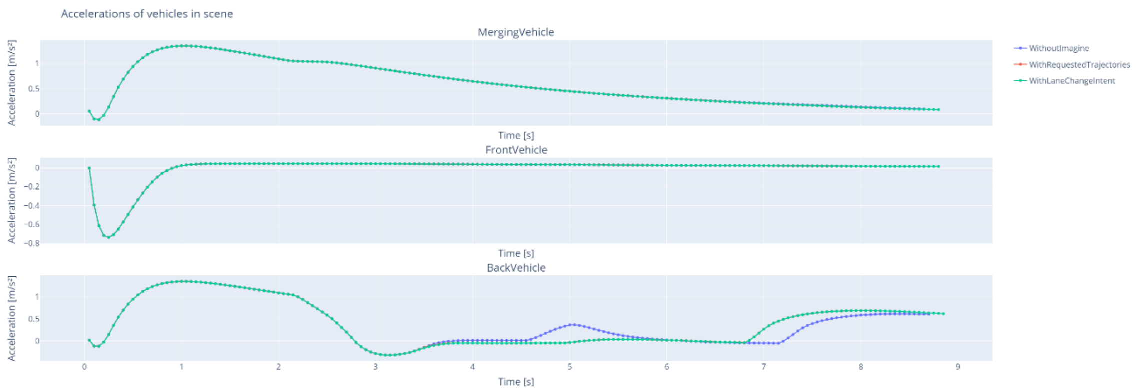


Figure 88: Balanced acceleration profile

4.5.2.6 Low speed waiver over a short period of time

Early cooperation involves only a minor acceleration sacrifice for the rear vehicle over a period of about 2 ½ seconds:

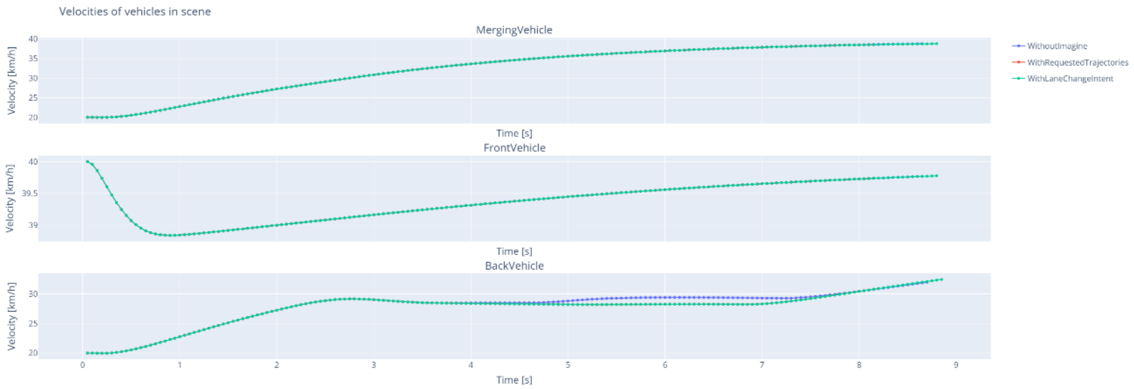


Figure 89: Low short-term speed waiver

4.5.2.7 Maintaining distance during cooperative lane changes

When the agreed, cooperative lane change begins, the lane change is started at an earlier point in time with a slightly shorter distance than in the scenario without IMAGinE. Subsequently, the distances in front of and behind the vehicle entering the gap are increased again:

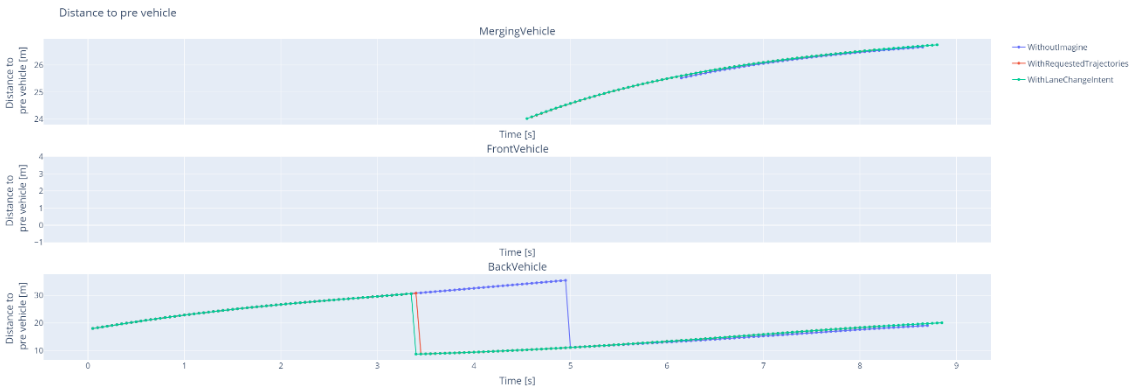


Figure 90: Keeping distance cooperative lane change

4.5.2.8 Time gaps during cooperative lane changes

A time gap is defined as distance divided by ego speed. It indicates the time in which the first-person vehicle has reached the current position of the vehicle in front. The faster the first-person vehicle travels, the proportionally more distance it must maintain from the vehicle in front in order to travel the same time gap. The recommendation "distance half speedometer" corresponds to a time gap of 1.8 seconds as a safety distance ahead. In everyday traffic, smaller time gaps of, for example, about 1.3 seconds are also driven in tied or dense traffic. Time gaps of less than one second are subject to regulatory sanctions in Germany if they are not only driven for a short time (e.g. during a lane change into a gap or during braking). If the differential speeds during lane changes are low, short time gaps of e.g. 0.3 seconds are not uncommon in everyday traffic. However, during and after a lane change, these gaps must be increased again to a permitted following distance of > 1 second.

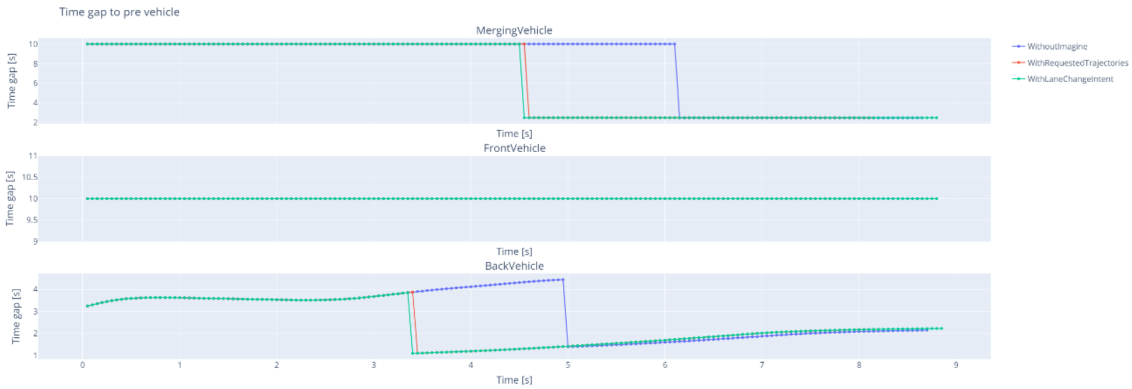


Figure 91: Safe time gap

In the test scenario, a safe time gap of just over one second is maintained throughout the lane change, which is gradually increased during and after the lane change by the acceleration of the reeler (in other scenarios additionally or alternatively by the deceleration of the following vehicle).

Thus, the test scenario shows a safe cooperative lane change in which the lane change is supported by small, short speed adjustments.

4.5.2.9 Verification F1 at highway entrance with ten vehicles

In the BMW driving simulation, among other things, a simulation scenario with ten intelligent vehicles equipped with Bbasic was presented and evaluated. In this scenario, several cooperations are agreed upon and executed in parallel. As a result, pairwise cooperations result in successful zipping into tight gaps. Sample screenshots of a video are reproduced below.

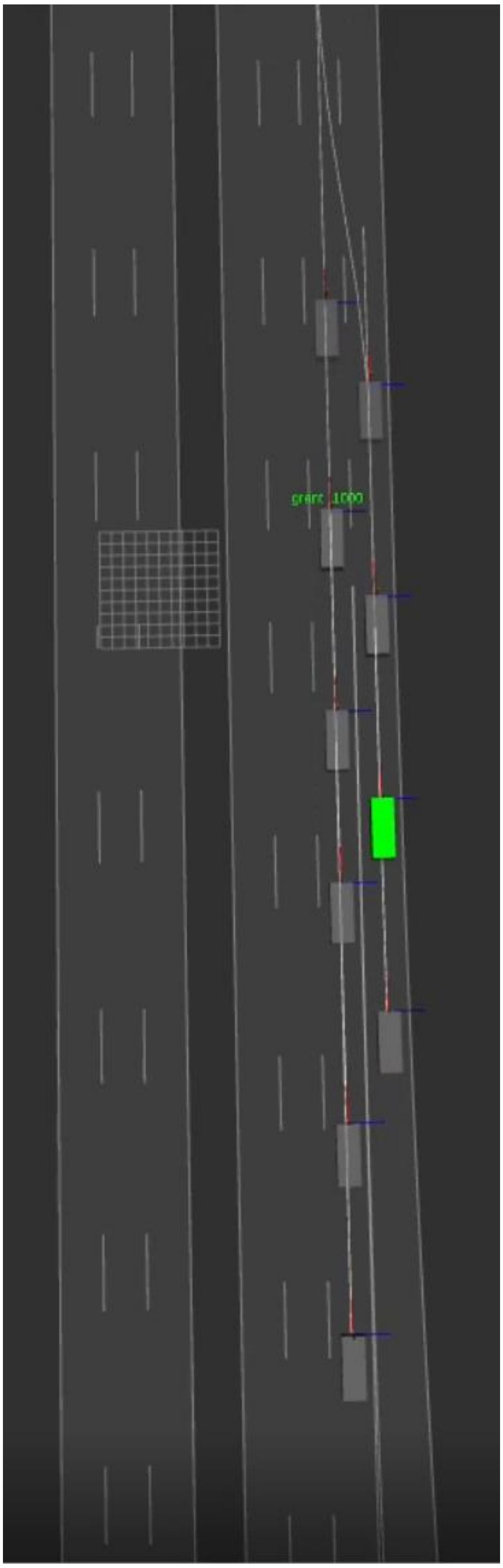


Figure 92: 5s: First grant to front enrollee

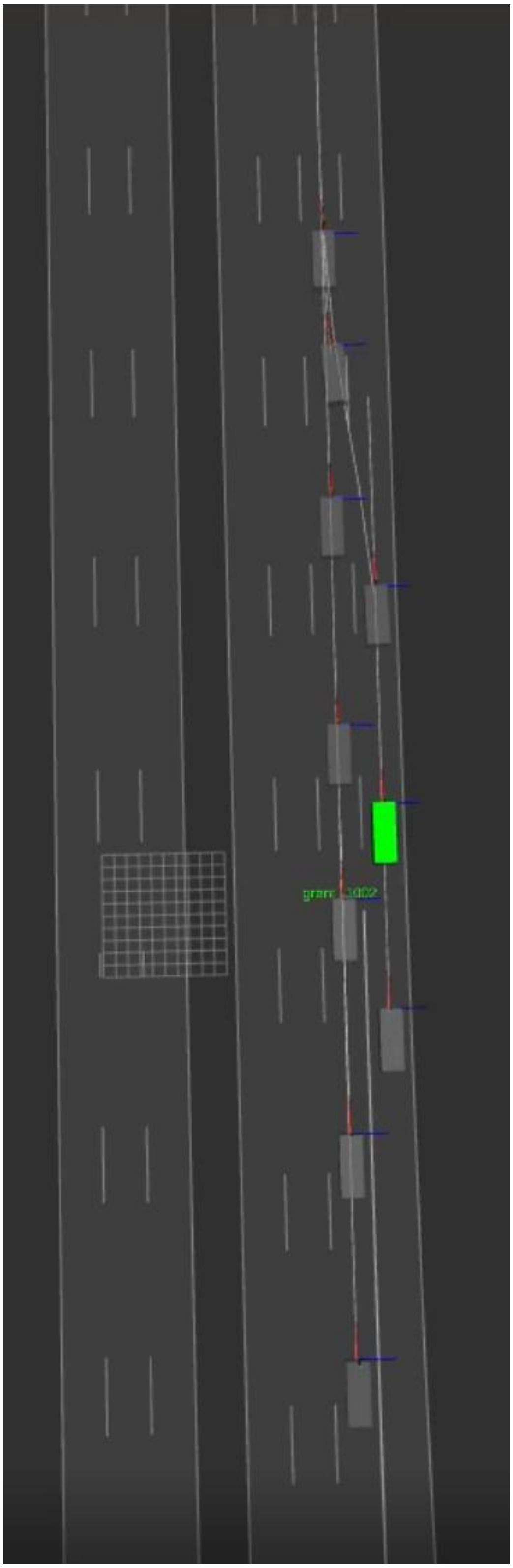


Figure 93: 8s: Second grant to second enrollee

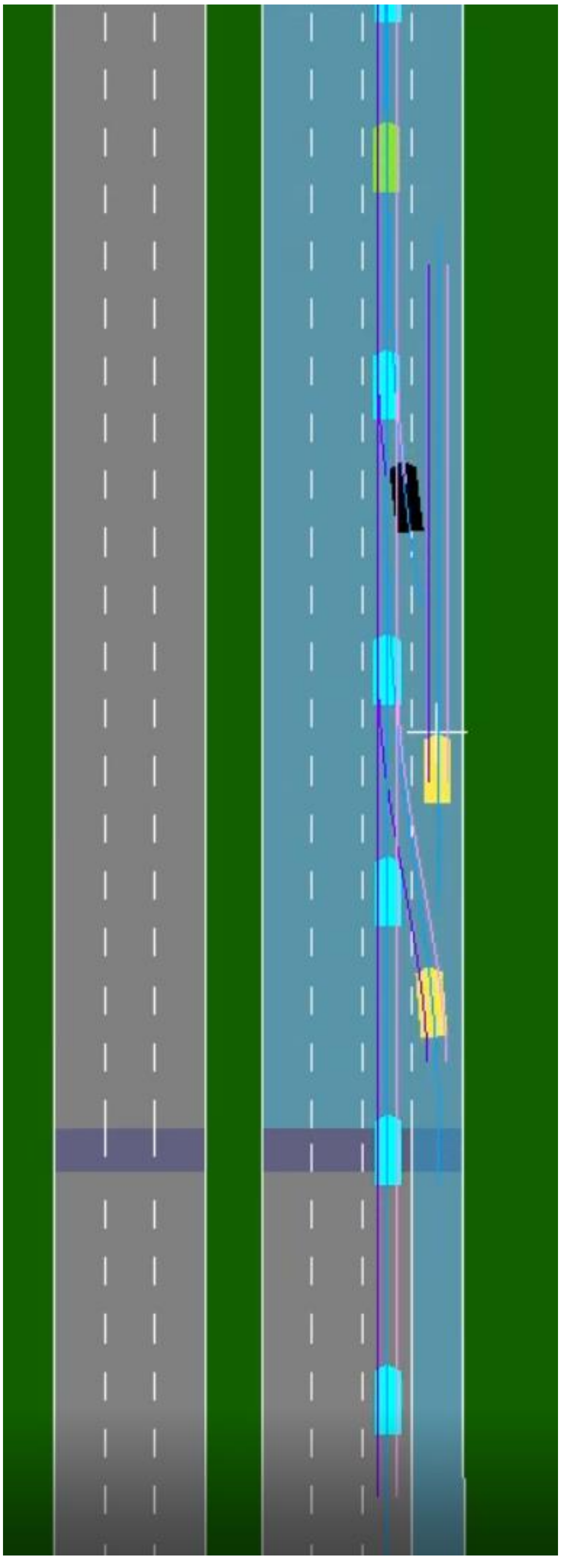


Figure 94: 10s: Lane changes planned and executed in parallel

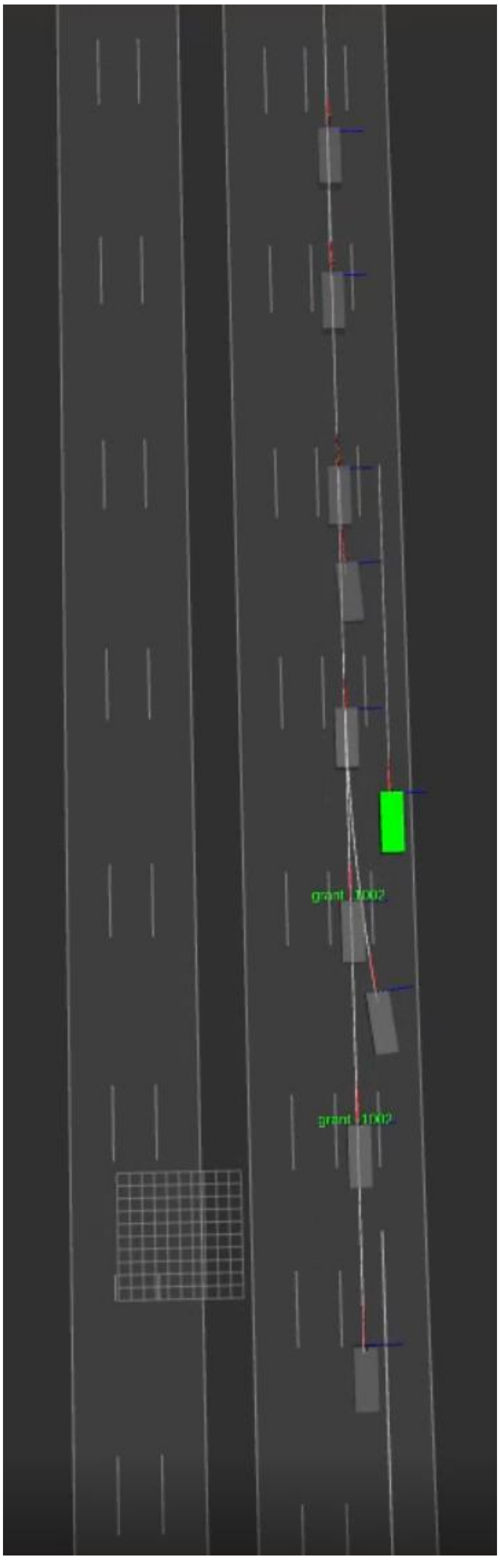


Figure 95: 11s: 3rd grant to third reeving unit by 2 cars

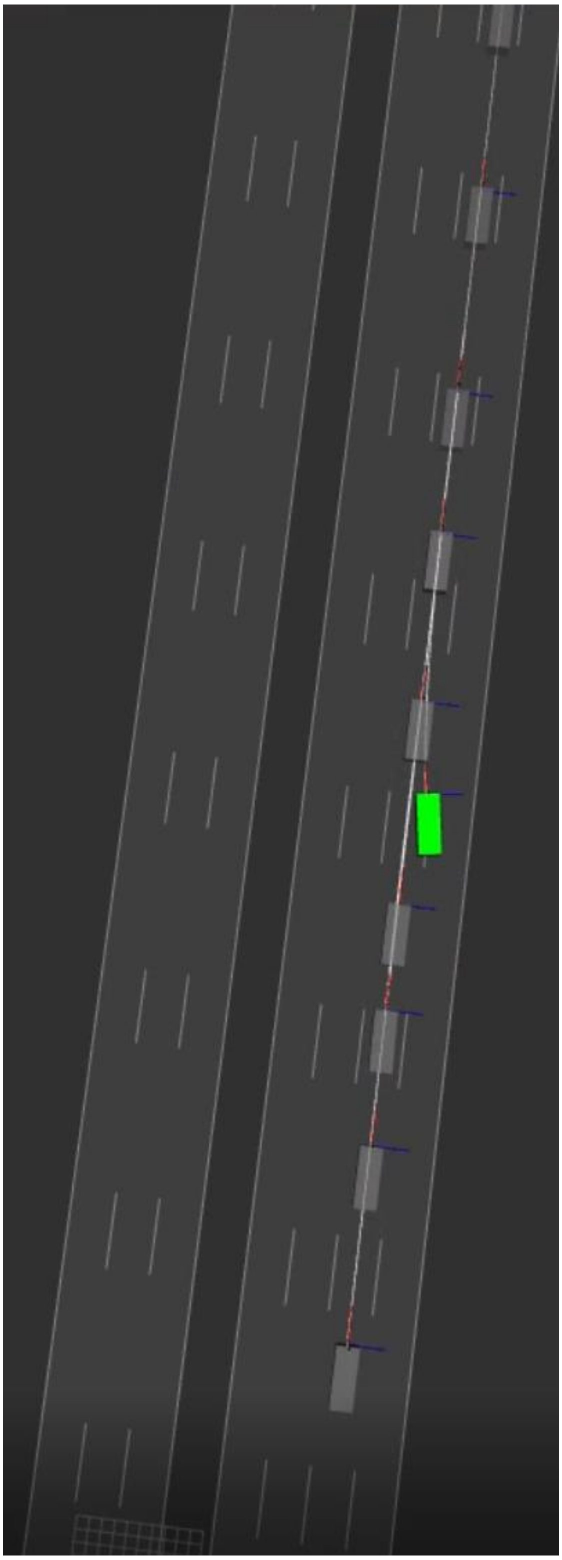


Figure 96: 15s: Reaching into narrow gap after tuning

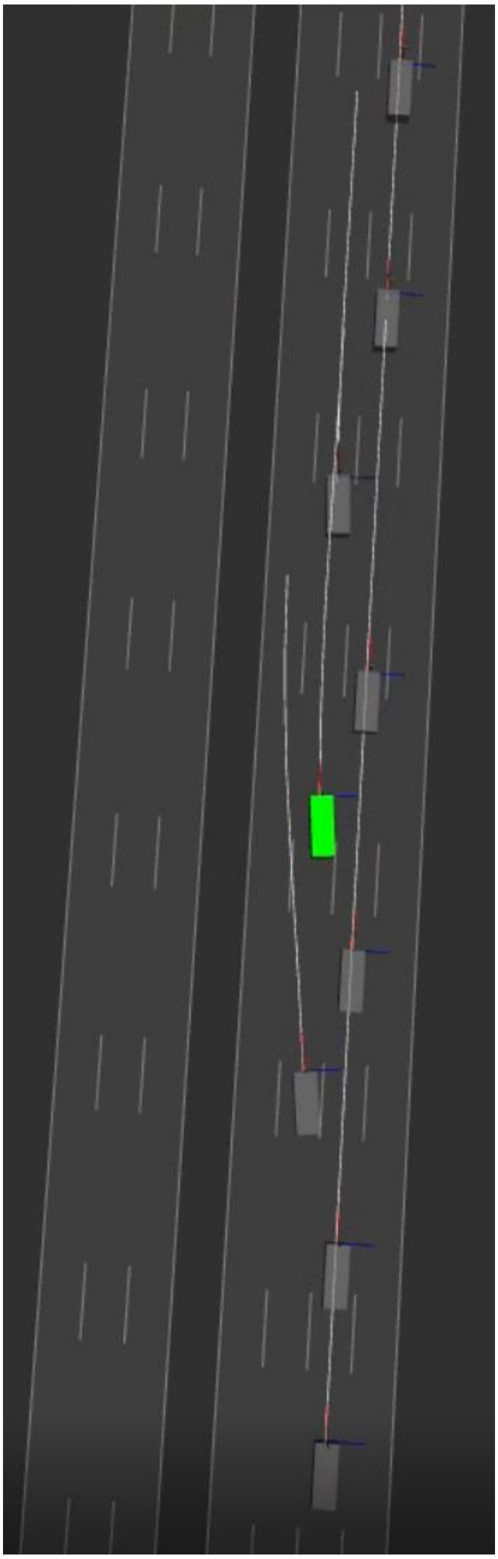


Figure 97: 20s: Increase of distances, resolution by further lane changes

4.5.4 Summary of the present results

As expected, early and fast maneuver coordination with the IMAGinE Bbasic procedure enables vehicles to cooperate earlier on the main carriageway. As a result, acceleration profiles can be more balanced. In the current design, a shortened distance at the start of reeving, which is nevertheless safe and even complies with stationary rules, is maintained with a time gap of just over one second throughout the entire maneuver. It is increased again shortly after the start of reeving. Further adaptation, for example to use even narrower gaps with a further shortened rear following distance for a short time, is just as possible as maintaining larger following distances by making corresponding parameter changes to the distance model.

The simulations carried out at BMW also show that cooperative driving also works without fast IMAGinE message exchange in the single-operator processes investigated, in that the need for cooperation of other vehicles is detected via the vehicle's own sensor system, evaluated, and then a suitable autonomous decision is made about the acceptability of the cooperation. The parameterizable driver behavior model used for this purpose, which reacts in a manner similar to a driver, is based exclusively on the currently known status data and the vehicle's own situation assessment. Automated vehicles can proceed in the same way.

4.6 Concept verification Mercedes-Benz AG/DCAITI

The proof-of-concept of the role-based voting concept was performed by Mercedes-Benz AG and DACITI in two different functions (F1, F2).

4.6.1 F1 Proof of Concept

For the proof-of-concept of function F1 - threading at highway interchanges, the simulation environment PHABMACS was extended by a module for coupling simulation and real data. This module can reproduce previously recorded real vehicles in the simulation, thus creating a simulated "real world scenario". With the help of this setup, the proof-of-concept of the maneuver coordination concept was carried out.

The following figure shows the threading area in the simulation. The surrounding vehicles, which are located on the main lanes, are vehicles from a real data set. The vehicles travel along the previously recorded trajectory, creating different maneuvering situations. The ego-vehicle is located in the merge lane and was also recorded from the dataset. In the simulation, the ego vehicle is replaced by a simulated vehicle. The starting conditions, such as the speed, the orientation or even the time of appearance, were taken from the real data set. Thus, a relation between the tuning concept in the simulation and the tuning done in the real data set can be investigated.

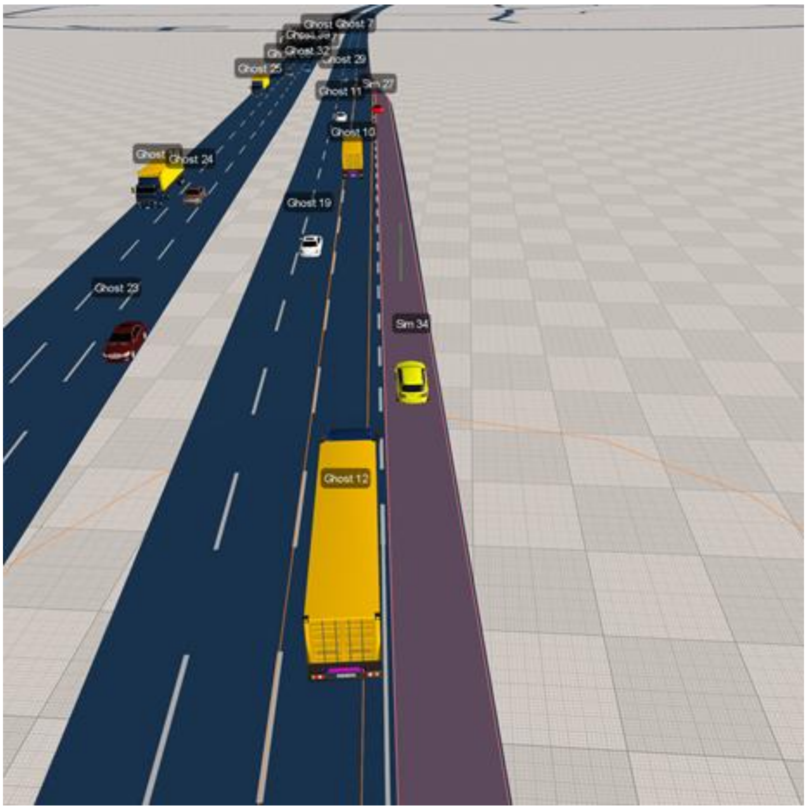


Figure 98: PHABMACS simulation Threading scenario

To display the state transitions, the current state of each vehicle in the simulation was visualized as a "merge state". The information is clearly arranged and lined up as text boxes in the lower simulation screen. Thus, the correct state sequence could be checked and validated. The following figure shows the states of the individual vehicles.

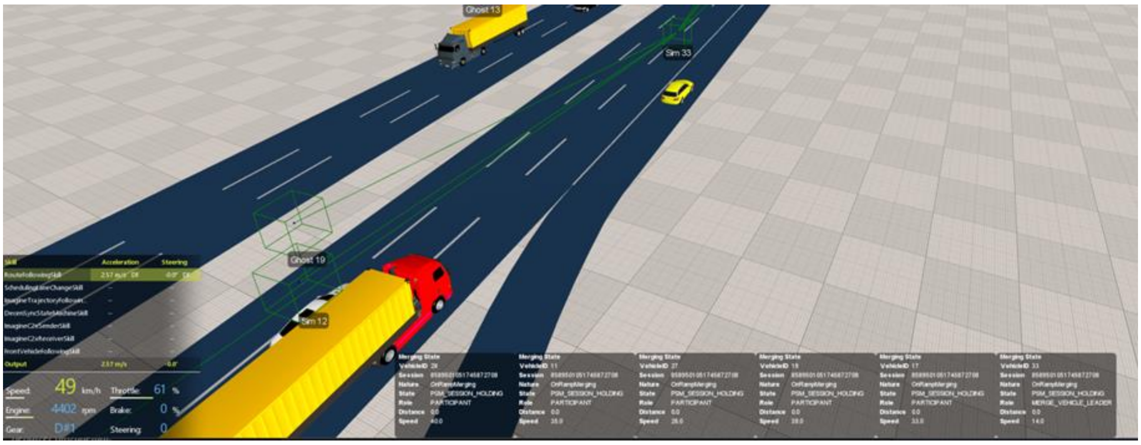


Figure 99: States of the participants in the simulation

The proof-of-concept was performed using a simplified V2X model. The messages were assigned a delay of 200ms from transmission to reception. Furthermore, the influence of a V2X package-lost rate on the application was investigated. For this purpose, the abort conditions, e.g. in case of a V2X module failure or a sudden communication abort with a subscriber, were implemented and tested. Two example scenarios were created to test the cooperative approach.

In the first example, the speed profile of the vehicles involved was recorded without the support of communication. The following diagram represents the recorded measurement data of the simulation.

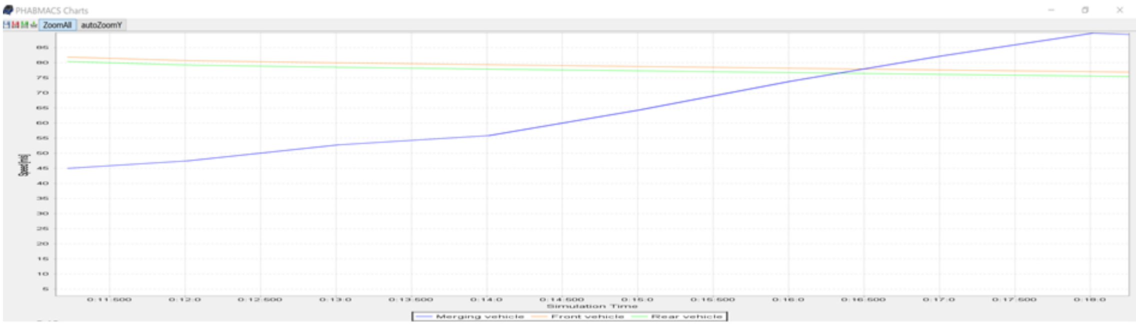


Figure 100: Speed diagram without cooperation

As can be seen, the ego vehicle (blue) is created with an initial speed of 45 km/h in the scenario. The speed is increased to approx. 90 km/h during the threading process. The two trucks drive almost at a constant speed of about 80 km/h on the right main lane. Based on the extended environment model, the ego vehicle can decide on a gap quite early and focus on it in the trajectory planner. This illustrates the increasing speed profile.

If the same example is now carried out with active V2X communication, the cooperative behavior becomes apparent. Due to the early communication establishment (from simulation time: 12 s) with the possible participants as well as the negotiation of the respective vehicle roles (front and rear vehicle), a cooperative behavior is shown in the simulation.

If the roles are negotiated, the vehicles move in a role-adequate manner. The front vehicle (orange) will accelerate a little if it has a clear lane and enough distance to its front vehicle. The rear vehicle (green) will not accelerate any more and will keep the speed constant or reduce it slightly (sail) if necessary. These small reactions have a strong effect on the threading parameters. Thus, the gap can be reached with an even smoother or more constant speed profile. The small cooperative maneuvers of the road users have a positive effect on the threading process.

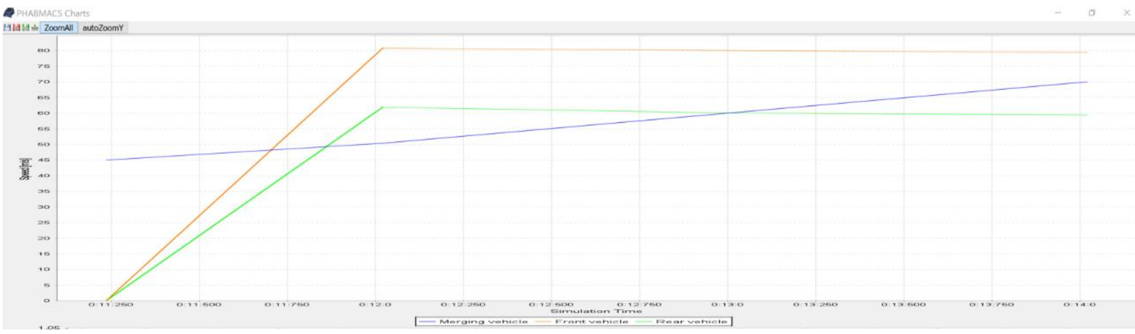


Figure 101: Speed diagram with cooperation

The investigations were carried out on further examples in the simulation, where similar improvements could be achieved. Further work will later extend the simulation environment with the maneuver coordination concept via a network simulation to test the limits of the concept as well as the feasibility with the current state of the art in the field of communication.

4.6.2 F2 Proof of Concept

The simulation environment PHABMACS has been extended by the driving function "Platooning". Vehicles equipped with this function can join, initiate and leave platoons via V2X. The following platoon scenarios were created in IMAGinE.

- Forming a platoon
- Dissolve a platoon
- Middle vehicle detaches from the platoon

These scenarios were implemented and tested in the simulation. The following figure shows the simulation environment PHABMACS with three vehicles driving in platooning. Each vehicle is equipped with a V2X communication interface, via which vehicle 1 (red) sends a request for platooning.

Figure 102: Platooning is formed

The other vehicles accept this and arrange themselves in the platoon. For this purpose, the distances are minimized. The middle vehicle now has the same distance to the front and rear vehicle.

Figure 103: Platooning is active - vehicles with equal spacing

The boxes and dashes symbolize the exchange via the communication interface of the vehicles. The colors show the current state of the respective vehicle. The legend for this can be found in the upper area of the image. As can be seen, the vehicles in Figure 103 are in the "Drive" platoon state.

The platooning can also be shown in the following diagram of the measured data.

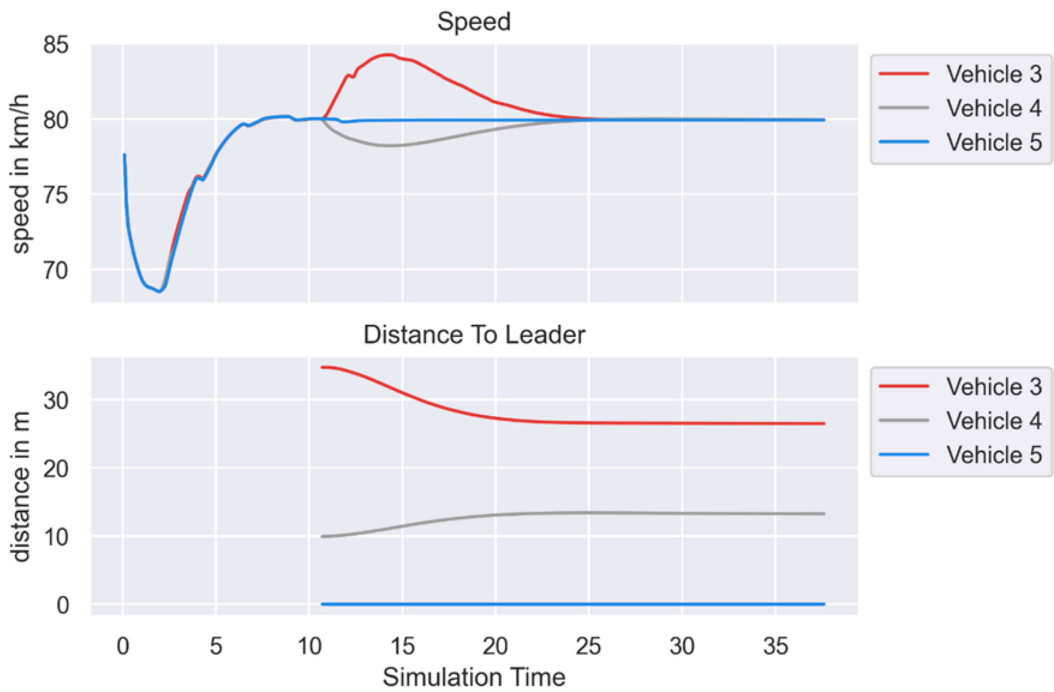


Figure 104: Speed and distance measurement in the platooning scenario

At the beginning of the scenario (10s), the vehicles are at similar speed, but with different distances to the vehicle in front. After the request as well as the confirmation of all other road users to the platoon, the last vehicle approaches the front vehicles. The middle vehicle positions itself exactly in the middle between the platooning participants. This can also be seen from the speed profile and the distance profile. The rear vehicle (red) increases its speed to reduce the gap - this reduces the distance to the vehicle in front. The middle vehicle (gray) slightly reduces its speed so that the distance to the vehicle in front is increased. At the end of the scenario (25s to 40s) the vehicles drive in the platoon, with the same speed and the same distance to each other.

4.7 Concept verification Autobahn GmbH

The concept verification of the F4 function consists of two components: First, the implementation of the F4 in the vehicle, and in particular the computation of the EgoScore as the core of the route selection, is validated using three test cases. Second, the traffic impact of the F4 is investigated in a macroscopic traffic simulation.

4.7.1 F4 Function validation in the vehicle

As described in the section "Maneuver coordination" in the concept presentation Autobahn GmbH (D2.5), the route selection of the vehicles in the cooperative-strategic traffic distribution is decided on the basis of a comparison of the EgoScores calculated individually by each vehicle. The score calculation thus represents the decisive component of the route selection.

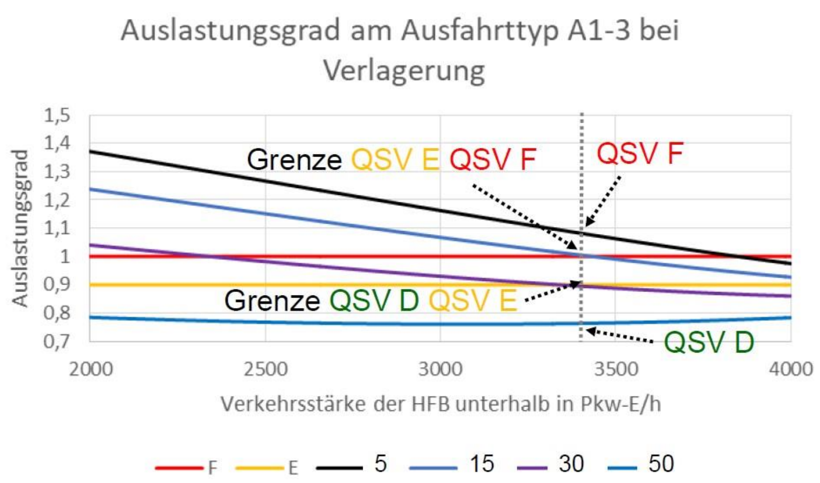
To validate the score calculation, the score-influencing parameters are changed and it is checked whether the voting result, in which the route choice of the vehicles is decided, matches the expected result. On the one hand, the two extreme cases are examined here. That is, the parameters are chosen in such a way that the vehicle under consideration is expected to continue on the main route (test case 1) or is chosen in such a way that a departure onto the alternative route is expected (test case 2). On the other hand, the case is investigated that all vehicles have exactly the same score (test case 3). The exact list of parameters, as well as an evaluation of the test cases can be found in Deliverable D4.4 (Highway (D4.4)).

4.7.2 F4 Traffic Impact

The main objective of the F4 concept is to optimize the distribution of traffic among route options so that traffic congestion is avoided and available capacity on the freeways and base network is utilized. Regarding the operation of F4, the focus of the expected outcome is the effect on the large-scale traffic condition. Since it is not possible to demonstrate this effect in the context of test routes, macroscopic traffic simulations can be classically used for this purpose. Thus, in order to verify the usefulness of the F4 function, a macroscopic simulation was developed representing real scenarios on German highways. For the modeling and evaluation, the technical regulations applicable in Germany as well as statistical data were considered in different steps of the procedure, as far as they are applicable and feasible. Examples are:

- Demand model (activities, travel routes, and O-D matrices) using statistical road user data:
  - Composition of vehicle groups and respective mileage (traffic in kilometers - VK) according to *Federal Motor Transport Authority statistics 2021*

   - Traffic behavior according to the nationwide *Mobility in Germany (MiD) 2017* survey by the BMVI
- Infrastructure model (spatial and temporal structure of the transport system and its elements).
   - Typification of intersections, expressways and the subordinate network according to the *Guidelines for the Design of Motorways (RAA).* This is particularly relevant for the generation of characteristic values in the evaluation step, but also specifies the applicable speed limits, number of lanes, etc.
- Analysis
   - The traffic engineering design of highways in Germany is based on the *Manual for the Design of Road Traffic Facilities HBS* (2015). This also includes the quality of traffic flow on freeways (*quality levels of traffic flow QSV*). As part of the evaluations in WP5.3, the effects of traffic shifts are examined according to F4 and corresponding statements are evaluated according to the QSV qualification scale in the HBS. An example of this is shown in the following figure. Quality levels of traffic flow are divided into levels A (good traffic quality) to F (poor traffic quality).



   - Evaluations and generated parameters according to the method manual for the Federal Transport Infrastructure Plan 2030
      - Change in operating costs
      - Change in exhaust gas loads according to HBEFA (Handbook Emission Factors for Road Transport)
      - Change in traffic safety
      - Change in travel time in passenger traffic

- Determination of q-V-diagrams for disturbed traffic flow by means of microscopic simulation (VISSIM) as input parameters for macroscopic simulation for calibration of congestion wave speeds, driven speeds and capacities

With the help of several test cases or scenarios, the applicability of F4 in different configurations was investigated step by step, among others also in comparison to classical traffic control practices. The detailed description of this, including the macroscopic simulation environment and results is given in deliverable D5.3.

5 SUMMARY AND OUTLOOK

The objective of work package AP2.5 was to summarize and process the work performed within the framework of subproject 2 (TP2). In the associated deliverable D2.5, the common IMAGinE components were presented as an overall system and necessary adjustments resulting from the simulation results were identified. In addition, all approaches and concepts for maneuver coordination developed in IMAGinE by the individual project partners were processed, tested and the results presented.

The work of subproject TP2 has made it possible to provide a common framework specification and common interfaces for IMAGinE functions F1 to F6. An implementation of the jointly specified, trajectory-based maneuver coordination procedure "IMAGinE 2018" based on this, realized in the joint subcontract GUA1, is available. The "proof-of-concept" of the maneuver reconciliation originally planned in work package AP2.5 could be successfully carried out on the basis of GUA1 after subsequent improvements only in individual test situations. The maturity of the implementation was insufficient for a deeper evaluation.

Therefore, the proof-of-concept required in WP2.5 was performed by the individual project partners for the maneuver coordination concepts developed within IMAGinE. The baseline implementations of each maneuver planner and coordination concept were verified in various simulation environments in a series of test scenarios for several IMAGinE cooperative functions. In addition, the common components of the IMAGinE architecture were presented as an overall system and necessary adjustments resulting as a result of the simulation were highlighted. The "proof-of-concept" was specifically performed and documented by each partner for the respective maneuver coordination concept. Thereby, both the applied methods of verification and the selection of the used IMAGinE functions and scenarios are partner specific. However, the basis of the maneuver coordination concepts implemented in IMAGinE is the same across all work. The general IMAGinE architecture, the cooperative environment model from joint subcontract 2 (GUA2), and the communication module are used for this purpose. The description of the technical basis can be found in chapter Technical Framework (D2.5).

During the course of WP2.5, the partner-specific maneuver coordination concepts from IMAGinE were integrated into simulators and verified using the six cooperative maneuver functions. An overview of the maneuver coordination concepts used and the functions used by the different project partners can be found in chapter Description Concept of IMAGinE Cooperative Maneuver Coordination (D2.5).

Summarizing all partners, it can be said that the mentioned conceptual approaches could be successfully verified with the "proof-of-concept" carried out in WP2.5 as a concept study. With all concepts, cooperations could be successfully carried out in simulation and/or in the vehicle based on the different functions. The project partners have successfully derived adaptations from their simulation results for the implementation available from GUA1 and for the partner-specific algorithms and have continuously developed the system in the following work packages.

The concepts integrated in WP2.5 will be handed over to Work Packages 5.3 and 5.4 for further evaluation of the study items.