D3.2

Cooperative maneuvring in the presence of hierarchical traffic management

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1. Introduction

1.1 About TransAID

As automated driving (AD) becomes feasible on interrupted and uninterrupted traffic flow facilities, it is important to assess its impacts on traffic safety, traffic efficiency, and the environment. During the early stages of AD market introduction, cooperative and automated vehicles (CAVs), automated vehicles (AVs) of different SAE levels, cooperative vehicles (CVs) able to communicate via vehicle-to-anything (V2X), and legacy vehicles (LVs) will share the same roads with varying penetration rates. In the course of this period, there will be areas and situations on the roads where high automation can be granted, and others where it will not be allowed or feasible due to system failures, highly complex traffic situations, human factors and possibly other reasons. At these areas, many AVs will have to change their level of automation. We refer to these areas as “Transition Areas” (TAs).

TransAID develops and demonstrates traffic management procedures and protocols to enable smooth coexistence of (C)AVs, CVs, and LVs, especially at TAs. A hierarchical and centralized approach is adopted, where control actions are implemented at different layers including traffic management centres (TMCs), roadside infrastructure, and vehicles.

Initially, simulations will be run to investigate the efficiency of infrastructure-assisted traffic management solutions in controlling (C)AVs, CVs, and LVs at TAs, taking into account traffic safety, traffic efficiency and environmental metrics. Then, communication protocols for the cooperation between (C)AVs – CVs and the road infrastructure are going to be developed. Traffic measures to detect and inform LVs will be also addressed. The most promising solutions will be subsequently implemented as real world prototypes and demonstrated at a test track (1st project iteration), or possibly under actual urban traffic conditions (2nd project iteration). Finally, guidelines for advanced infrastructure-assisted driving will be formulated. These guidelines are going to include a roadmap defining necessary activities and upgrades of road infrastructure in the upcoming fifteen years to guarantee a smooth coexistence of (C)AVs, CVs, and LVs.

1.1.1 Iterative project approach

TransAID develops and tests infrastructure-assisted management solutions for mixed traffic ((C)AVs, CVs, and LVs) at TAs in two project iterations. Each project iteration lasts half of the total project duration. During the first project iteration, focus is placed on studying Transitions-of-Control (ToCs) and Minimum Risk Manoeuvres (MRMs) using simplified scenarios. To this end, models for AD and ToC/MRM are adopted and developed. The simplified scenarios are used for conducting several simulation experiments to analyse the impacts of ToCs at TAs, and the effects of the corresponding mitigating measures.

During the second project iteration, the experience accumulated during the first project iteration is used to refine/tune the driver models and enhance/extend the proposed mitigating measures. Moreover, the complexity/realism of the tested scenarios will be increased and the possibility of combining multiple simplified scenarios into one new more complex Use Case (UC) is considered.

1.2 Purpose of this document

The scope of Deliverable D3.2 encompasses two main tasks. The first task relates to the introduction of a cooperative manoeuvring framework and its simulation in the microscopic traffic simulator Simulation of Urban MObility (SUMO). The cooperative manoeuvring framework involves cooperation between two CAVs (ego CAV – target follower CAV) in the form of gap creation from the target follower CAV side. To this end, two different cooperative manoeuvring approaches are developed: a centralized approach, where negotiation of manoeuver coordination is performed through the TMC and implemented by the roadside infrastructure (RSI) via infrastructure-to-vehicle (I2V) communications, and a decentralized one where CAVs establish direct cooperation between them with the use of vehicle-to-vehicle (V2V) communication. The logic and required functions for the implementation of cooperative manoeuvring in SUMO are also presented. Cooperative manoeuvring is explicitly described in the context of Scenario 3 (Apply traffic separation before motorway merging/diverging) since its mechanism is similar among the examined scenarios. The second task relates to the adaptation and fine-tuning of the AV/driver models proposed in Deliverable D3.1. These models are adapted to account for high fidelity communication protocols which will be evaluated with the use of the simulation platform iTETRIS. Finally, the implications of the real-world testing of the TransAID use cases are taken into consideration for the fine-tuning of the AV/driver models.

1.3 Structure of this document

Deliverable D3.2 is comprised of six sections. Section 1 is the introductory section where we present a summary of the project, describe the purpose of this document, and provide its structure along with the Glossary. The state-of-the art with respect to cooperative manoeuvring is presented in Section 2 in conjunction with a brief introduction of the TransAID approach. Section 3 provides a detailed description of the TransAID proposed cooperative manoeuvring approaches (centralized and decentralized). Coupling with hierarchical traffic management and communications is also discussed in Section 3. The newly developed SUMO functions (TraCI commands) for the implementation of the cooperative manoeuvring logic in SUMO are presented in Section 4. A description of cooperative manoeuvring in the context of Scenario 3 (Apply traffic separation before motorway merging/diverging) is presented in Section 4 as well. Section 5 addresses the adaptation of AV/driver models to cope with the higher fidelity simulations (iTETRIS) where detailed communication protocols are considered, and the fine-tuning of AV/driver models with respect to the implications of the real world testing of the TransAID use cases. Finally, Section 6 concludes Deliverable D3.2 providing outlooks for future work during the 2nd project iteration.

1.4 Glossary

Abbreviation/Term	**Definition**
ACC	Adaptive Cruise Control
AD	Automated Driving
AV	Automated Vehicles
CACC	Cooperative Adaptive Cruise Control
CAM	Cooperative Awareness Message
CAV	Cooperative Automated Vehicle
CLCS	Cooperative Lane Change Service
CPM	Collective Perception Message
CV	Cooperative Vehicle
DX.X	Deliverable X.X
I2V	Infrastructure-to-vehicle
IDM	Intelligent Driver Model
LV	Legacy Vehicle
MCM	Manoeuvre Coordination Message
MCS	Manoeuvre Coordination Service
MIQP	Mixed-Integer Quadratic Programming
MRM	Minimum Risk Manoeuvre
RSI	Roadside Infrastructure
SUMO	Simulation of Urban MObility
TA	Transition area
TraCI	Traffic Control Interface
TMC	Traffic Management Centre
ToC	Transition of Control
TransAID	Transition Areas for Infrastructure-Assisted Driving
UC	Use Case
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-anything

2 Cooperative Driving State-of-the-Art

AVs are equipped with on-board sensors (RADARs, LIDARs, GNSS, and Cameras) that enable them to perceive the road environment and to plan and follow their trajectory accordingly. In the course of the planned trajectory, AVs use sensory information to assist tactical manoeuvres for obstacle avoidance or speed gain reasons. Lately, few AVs are also programmed to predict the future actions of other road users and plan/adjust their trajectories respectively (Bansal, Krizhevsky, & Ogale, 2018). However, in general the majority of AVs will only be capable to locally interpret the future intentions of the other vehicles (including AVs): exact and reliable knowledge of other vehicles intentions is not possible without connectivity capabilities. The absence of connectivity leads AVs to operate under conservative conditions, like for example applying lower speeds or higher gaps in such a way to enforce safety to the highest extent. Nevertheless, the integration of communications in AV technology can empower the exchange of messages among CAVs with respect to planned trajectories, future intentions and cooperative sensing information. Thus, CAVs will be able to explicitly negotiate/coordinate and subsequently execute their actions to achieve an increased level of safety and traffic flow performance. Cooperative driving is primarily researched in the context of the following situations:

- solving the coordination problem at intersections,
- control for lane change and merge manoeuvres,
- maximizing throughput by quickly reaching a platooning state,
- overtaking scenario, and
- emergency situations

Initially, cooperative driving approaches were designed to address manoeuvre specific scenarios. A cooperative lane change service (CLCS) that addresses the cooperative lane change case was presented by (Hobert et al., 2015) in the context of the Autonet2030 project. CLCS allows the negotiation of manoeuvres among vehicles and enables relative space reservation for the implementation of the cooperative lane change that is comprised of three phases. In the search phase, the ego vehicle announces to surrounding vehicles its intention to cooperate. Surrounding vehicles that consider cooperation suitable reply to the ego vehicle request. The ego vehicle will finally decide on the best peer vehicle to coordinate actions with and will provide relevant information to all neighbouring traffic in the lane change area. In the preparation phase, the peer vehicle creates space to the ego vehicle to facilitate the cooperative lane change. When a safe gap for merging has been created the ego vehicle is informed that the execution phase can begin. In this final phase, the ego vehicle implements the lane change manoeuvre. If safety-critical situations arise, the cooperative lane change manoeuvre can be aborted with the transmission of a corresponding dedicated message.

The i-GAME project also introduced manoeuvre-specific methods to tackle the following cooperative driving challenges: a) cooperative platoon merging, and b) cooperative intersection control (Englund et al., 2016). In the case of cooperative platoon merging a cooperative manoeuvring protocol was established that encompasses the following actions: 1) synchronization of platoons' speeds, 2) pairing between vehicles of the two platoons (simultaneous or sequential), 3) creation of gaps between the respective vehicle pairs, and 4) confirmation of gaps and platoon merging. In the case of the cooperative intersection control, the concept of “virtual platoons” was adopted. Virtual platoons are specific formations of vehicles that hold platoons-specific properties but are spatially distributed over perpendicular dimensions within the intersection area. Vehicle information is communicated upon entrance in the intersection conflicting zone (“competition zone”) for the creation of the virtual platoon. After the formation of the virtual platoon, the virtual gaps are created, and finally vehicles continue driving in cooperative adaptive cruise control (CACC) mode. The sequence of vehicles in the virtual platoon is dictated based on the order of vehicle entrance in the competition zone, the priority of the driving lane, and the vehicles’ intentions.

A controller that coordinates CAV actions for the implementation of cooperative lane changing was introduced by (Bai, Zhang, & Hu, 2018). In this study, the cooperation is realized in the form of gap creation from the following CAV on the target lane. The logic of the controller is designed so that coordination can occur when: a) ego vehicle and target follower are CAVs, and b) ego vehicle, target follower and target leader are CAVs. Model predictive control is used for the formulation of the optimal control problem, which is solved with the use of a dynamic programming based numerical algorithm previously developed by the same researchers. The controller is tested against human driving (Intelligent Driver Model – IDM) along a two-lane arterial. The vehicle model parameters are set to fixed values both for the cooperative lane changing and for human driving case. The research assumes that the ego CAV is in the middle of the target follower and target leader in the beginning of the experiments. Simulation results were obtained for different initial headways between the target leader and target follower. This research showed that the cooperative lane changing controller can reduce the traffic oscillation of the lane changing vehicle (ego CAV) in any case, while benefits are realized for the target follower if the initial headway is below 4.5 s.

Recently, frameworks that can accommodate several cooperative driving scenarios in a generic way were also introduced. For instance, an approach for cooperative motion planning of CAVs based on Mixed-Integer Quadratic Programming (MIQP) was proposed by (Burger & Lauer, 2018). It is designed to coordinate the manoeuvers of a group of CAVs under non-safety critical traffic situations. The objective of the MIQP based approach is to minimize a cost function that considers rider’s comfort, energy and travel time savings. The MIQP based approach can trace the whole solution space and provide global optimum solutions, in contrast to previously applied priority based approaches. The researchers selected a quadratic cost function and linear vehicle dynamics model to simplify the solution complexity of the Mixed-Integer Program. The proposed MIQP formulation is applied in an overtaking scenario on a two-lane rural road with oncoming traffic, and is compared against a priority based approach and a non-cooperative motion planning approach. The experiment results show that the MIQP approach can guarantee the execution of the cooperative overtaking manoeuver with the minimum cost (involved CAVs maintain their desired speed during cooperative manoeuvring) among the examined approaches. However, it is also proven that the proposed approach is not real-time capable when the number of considered CAVs for the cooperative manoeuvring increases.

A scenario-independent manoeuvre coordination approach was also proposed by (Lehmann, Günther, & Wolf, 2018). The authors used the concept of Frénet frames to mathematically express planned and desired vehicle trajectories. The approach is divided into three phases. In the first phase, the need for manoeuvre coordination is assessed. This occurs when a CAV’s planned trajectory intersects with another CAV's planned trajectory or is obstructed by an obstacle. If the need for coordination is detected, a negotiation phase begins among the subject CAV and surrounding CAVs. During this second phase, the subject CAV computes a desired (optimal) trajectory and communicates it to neighbouring CAVs. Any CAV receiving the latter desired trajectory assesses if it can modify its planned trajectory based on a set of factors (driving comfort, delay etc.) to facilitate the subject CAV's desired trajectory. If cooperation is granted, the subject vehicle CAV updates its planned trajectory to become its desired trajectory and the cooperative manoeuvre is executed. Implementation of cooperation in the execution phase might temporarily break the right of way rules: for example, a faster incoming vehicle on the left lane might accept to slow down to let a vehicle overtake an obstacle on the right lane. Although the proposed approach can be scenario- and application-agnostic, there are still several challenges that have to be addressed pertaining to the resolution of corner cases, communication and standardization issues, and finally trajectory generation rules.

The focus of TransAID during the 1st project iteration explicitly resides on the development of a scenario-specific cooperative manoeuvring framework that facilitates lane change and merge manoeuvres. The framework embodies both a centralized and decentralized cooperative manoeuvring approach. Cooperative manoeuvring is explicitly investigated in the form of gap creation by the follower CAV to facilitate merging of the ego CAV onto the desired target lane. The latter cooperative manoeuvre type applies to the majority of the examined TransAID scenarios and can be easily replicated in a simulation environment. Cooperative manoeuvres of higher complexity (involving several concurrent actions from the cooperating vehicles) will be simulated during the 2nd project iteration, when manoeuvre-generic methods for vehicle cooperation will be also explored.

3 Modelling Cooperative Manoeuvering of CAVs

3.1 Cooperative Manoeuvring Framework

Cooperative manoeuvring in TransAID encompasses negotiation of actions between the ego CAV and the following CAV on the target lane. In the case that manoeuvre cooperation is agreed, the target follower CAV decelerates in order to create a safe gap for the ego CAV to merge on the target lane. Cooperation is warranted only when all vehicles surrounding the ego CAV (current follower, target leader, and target follower) are CAVs as well (**Figure 1, (B)**). Otherwise, cooperation is not feasible since the ego CAV is unaware of the intentions of its neighbouring CAVs which might disrupt cooperation if they execute an unexpected and sudden manoeuvre (**Figure 1, (A)**).

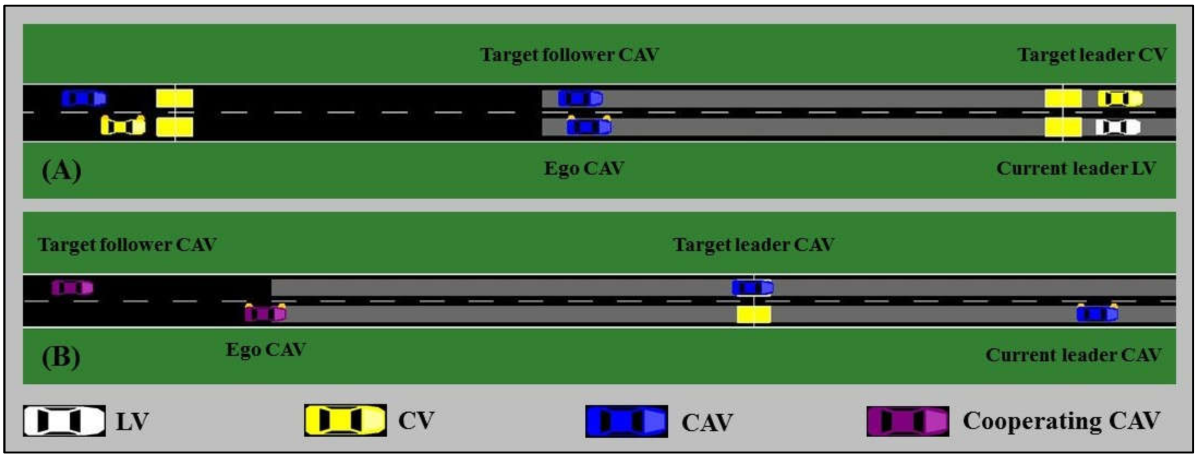

Figure 1. (A) Vehicle cooperation cannot be implemented since every neighbouring ego CAV vehicle is not CAV. (B) Vehicle cooperation is possible since the ego CAV is surrounded by CAVs.

On the other hand, the impacts of cooperative manoeuvring on surrounding traffic are not assessed in advance so as to identify whether cooperation is beneficial for every vehicle in the traffic stream or not. Namely, no optimization framework is applied to ensure that manoeuvre cooperation satisfies global optimum conditions in terms of traffic flow performance. TransAID developed both a centralized and a decentralized approach regarding cooperative manoeuvring. In the first case, the TMC that initiates cooperative manoeuvring and acts as the intermediate negotiating entity between the cooperating CAVs, while in the latter case, the ego CAV directly requests cooperation from the target follower CAV through V2X communication without the intervention of the TMC. Both approaches are presented in the flowcharts depicted in **Figure 2**.

As aforementioned, centralized cooperative manoeuvring presumes that the TMC requests cooperation when it has identified that the vehicles surrounding ego CAV are also CAVs. Moreover, negotiation of cooperation is conducted through the TMC, since the target follower CAV has to acknowledge to the TMC that it approves cooperation and subsequently the TMC will inform the ego CAV that the target follower CAV agrees to yield right-of-way and create a safe gap to facilitate merging. Hence, according to the centralized approach flowchart (**Figure 2**) the TMC will investigate cooperative manoeuvring possibility when the ego CAV fails to execute previous lane change advice dictated by the applied traffic management strategy. In this case, the centralized cooperative manoeuvring is considered as the last opportunity to facilitate the implementation of the advised lane change manoeuvre. The TMC identifies the surrounding ego CAV vehicle types through cooperative awareness (CAM), collective perception (CPM), sensor data and data fusion. If all surrounding vehicles are CAVs the TMC requests cooperation in the form of gap creation by the target follower CAV. The target follower CAV subsequently responds to the TMC either positively or negatively (we assume that the target follower CAV will be always willing to cooperate in the 1st iteration simulation experiments). If it finally agrees to create the requested gap it conveys its intention to the TMC which in turn notifies the ego CAV that cooperation has been acknowledged. Once the target follower CAV has created a safe gap (constantly monitored by the ego CAV) then the ego CAV merges on the target lane.

On the contrary, when a decentralized approach is followed, the ego CAV will directly ask for cooperation from the following CAV on the target lane. Thus, although the TMC receives information regarding the vehicle actions and intentions it does not eventually play a central role in the coordination of cooperative manoeuvring (TMC oversees but does not intervene in the cooperative manoeuvring process). The target follower CAV will either acknowledge the cooperation request or not and directly inform the ego CAV about its intentions. If cooperation is granted, the target follower CAV will decelerate to create the required safe gap for the ego CAV to merge on the target lane.

The planning of cooperative manoeuvring in the decentralized approach is limited by the sensor view of the interacting vehicles. Thus, on the boundaries of vehicle cooperation sub-optimal conditions might be induced to neighbouring traffic. This phenomenon can be exaggerated when multiple decentralized cooperative manoeuvres are concurrently executed in close proximity. On the other hand, TMC can acquire an enhanced perception with respect to vehicle dynamics and location information over a broader area due to cooperative awareness, collective perception, sensor data and data fusion. Hence, when a centralized approach is adopted, cooperative manoeuvring can be proactively planned and executed more smoothly without negatively impacting non-cooperating vehicles. This approach can also facilitate multi-agent manoeuvre coordination to ensure increased traffic flow performance. Thus, the centralized approached is also part of the TransAID proposal with respect to cooperative manoeuvring. However, focus will be placed on the investigation of manoeuvre-generic methods for vehicle coordination that consider multiple interacting vehicles during the 2nd project iteration.

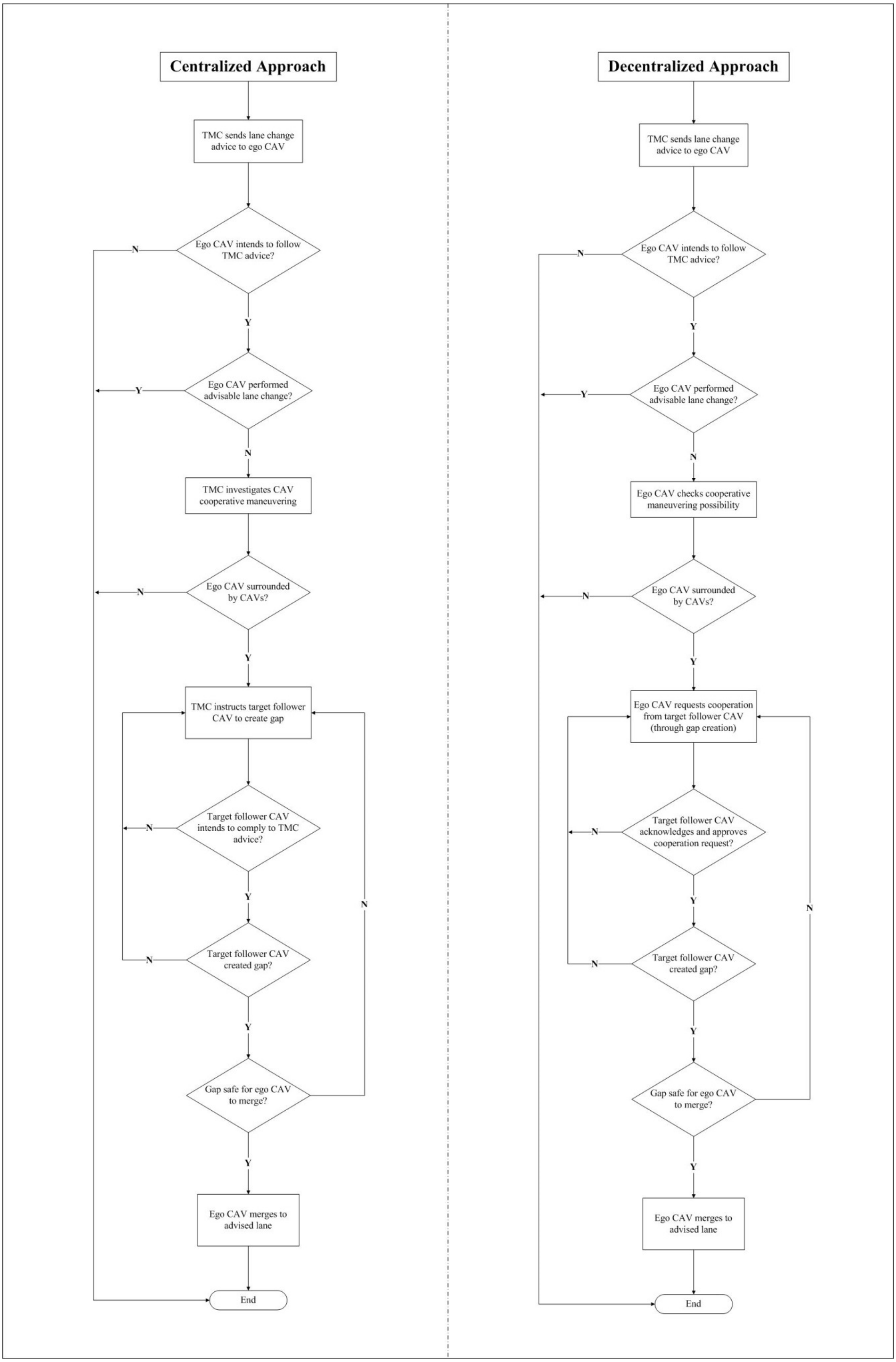

Figure 2. Centralized and decentralized cooperative manoeuvring approaches in TransAID.

3.2 Coupling with Hierarchical Traffic Management

The triggering conditions regarding cooperative manoeuvring were abstractly defined in the timeline of actions developed per examined scenario in Deliverable D2.2 (Wijbenga et al., 2018). In Deliverable D4.2 (Maerivoet et al., 2019) we elaborated on these conditions per traffic management service proposed by TransAID. The conditions were specified in the flowcharts that were developed separately for each scenario (cf. Sections 2.1, 2.2, 2,3, and 2.4 of Deliverable D4.2), and differ according to the road network geometry and source of traffic disruption (work zone, merge area, no automation zone etc.). They are briefly described in **Table 1**.

Table 1. Triggering conditions for cooperative manoeuvring per scenario.

Scenario ID	Triggering Conditions
Scenario 1	The TMC provides path information to the ego CAV so that it can use the free bus lane to pass the work zone without disengaging driving automation systems. The ego CAV attempts to move to the free bus lane but it is blocked by surrounding CAVs. Cooperative manoeuvring is applied to facilitate the ego CAV lane change manoeuver.
Scenario 2	The on-ramp ego CAV attempts to merge to the right-most mainline lane but is blocked by surrounding vehicles. If neighbouring vehicles are also CAVs cooperative manoeuvring is applied to aid the ego CAV merging onto the mainline lanes.
Scenario 3	A traffic separation policy is applied to prevent CAV disengagements in the vicinity of a highway merge area. An approaching ego CAV drives on the non-CAV designated lane. The TMC provides lane change advice to the ego CAV. The ego CAV attempts to shift to the CAV designated lane but is blocked by surrounding CAVs. Cooperative manoeuvring is applied to facilitate the ego CAV lane change manoeuver.
Scenario 4	The TMC sends lane change advice to the ego CAV so that it merges to the free lane and passes the work zone without disengaging driving automation systems. The ego CAV attempts to move to the free lane but it is blocked by surrounding CAVs. Cooperative manoeuvring is applied to facilitate the ego CAV lane change manoeuver.
Scenario 5	Cooperative manoeuvring is out of scope with respect to Scenario 5. In this scenario we investigate the distribution of ToCs upstream of a no automation zone to ensure increased traffic flow performance. Thus, mandatory lane changes are not required from the CAV side that would warrant cooperative manoeuvring in the case of blocking neighbouring vehicles.

Cooperative manoeuvring can encompass different possible actions from the cooperating CAVs. These actions can be either performed individually or in combination. Moreover, they can occur as an outcome of advice from the TMC side (centralized approach), or as the result of the direct negotiation between/among CAVs (decentralized). The list of possible actions is presented below:

- Target follower CAV decelerates to create gap
- Target follower CAV changes lane to create gap
- Ego CAV accelerates/decelerates to reach gap
- Target leader accelerates to create gap

According to the examined traffic situation, limitations might apply to the execution of the possible actions for the realization of cooperative manoeuvring. For example, in a highway merge area with multiple mainline lanes (TransAID Scenario 2 – Prevent ToC/MRM by providing speed, headway and/or lane advice) the target follower CAV might be able to change lane to its left lane in order to create gap for the ego CAV to merge on the mainline. On the contrary, on a two-lane road where one lane is closed due to work zone the target follower CAV driving on the free lane cannot change lane to facilitate the ego CAV lane change manoeuver. The feasible cooperative manoeuvring actions per examined scenario are shown in **Table 2**.

Table 2. Feasible cooperative manoeuvring actions per TransAID scenario.

Vehicle	Action	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Target follower	Decelerate	✓	✓	✓	✓	n/a
Target follower	Lane Change	✓	✓	✕	✕	n/a
Ego CAV	Accelerate/Decelerate	✓	✓	✓	✓	n/a
Target Leader	Accelerate	✓	✓	✓	✓	n/a

In Deliverable D3.2 (1st project iteration) we explicitly model and simulate cooperative manoeuvring in the form of gap creation from the target follower CAV. The modelling framework was previously presented in Section 3.1, while the simulation of the respective vehicle actions is described in Section 4. Since the cooperative manoeuvring mechanism is common for Scenarios 1 – 4 in the 1st project iteration the interactions between CAVs (ego CAV – target follower CAV) are discussed explicitly for Scenario 3 in Section 4.1. In the second version of Deliverable D3.2, we will look into complex cooperative manoeuvring cases, which concurrently consider higher vehicle interactions.

3.3 Coupling with Communications

Deliverable D3.2 deals with the execution of the cooperative manoeuvring in the traffic simulator SUMO (Lopez et al., 2018). The communication aspects of cooperative manoeuvring are comprehensively covered in Deliverable D5.2 (Correa et al., 2019). In the latter deliverable, the flow of Manoeuvre Coordination Messages (MCM) is introduced for both the centralized and the decentralized cooperative manoeuvre approaches. In the centralized approach, MCMs are exchanged between the infrastructure and the cooperating CAVs, while in the decentralized approach MCM exchange is explicitly executed among the interacting CAVs. The MCM containers that are used for the implementation of each approach are also determined. Finally, the developments proposed with respect to the execution rules and communication protocols of cooperative manoeuvring will be integrated in the simulation platform iTETRIS (Rondinone et al., 2013), where vehicle cooperation will be evaluated considering the influence of detailed communication protocols.

4 Simulation of Cooperative Manoeuvring

The simulation of the aforementioned cooperative manoeuvring framework (cf. Section 3) in SUMO requires the development of new Traffic Control Interface (TraCI)[1] commands. According to the cooperative manoeuvring logic presented in **Figure 1**, the following conditions should be met:

- ego CAV determines neighbouring vehicles blocking its desired lane change
- ego CAV knows the types (CAV, CV, or LV) of the neighbouring vehicles
- surrounding vehicles blocking the ego CAV desired lane change manoeuver are CAVs

Therefore, a TraCI command is developed that retrieves the IDs of the vehicles blocking the ego CAV from a potentially desired lane change manoeuver[2]. The IDs of the blocking vehicles include the name of their respective types. Hence, it can be identified whether neighbouring blockers are CAVs or not. The parameters used in the TraCI command that returns information with respect to neighbouring vehicles of a reference vehicle are show in **Table 3**.

Table 3. Parameters used in the TraCI command that retrieves information about neighbouring vehicles.

Parameter	Description
Vehicle ID	The ID of the reference vehicle.
Mode	Bitset (three bits) indicating which neighbouring vehicles should be returned.
Bit #1	Zero returns right neighbours; One returns left neighbours
Bit #2	Zero returns preceding neighbours; One returns following neighbours
Bit #3	Zero returns blocking neighbours; One returns all neighbours

If the latter command indicates that the target follower is a CAV and that surrounding vehicles affecting (blocking) the ego CAV are also CAVs, then the target follower CAV can create a gap with reference to the ego CAV in order to facilitate its desired lane change manoeuver. To facilitate the creation of gap between two specific vehicles in SUMO a new TraCI command named “open gap”[3] is developed. This command temporarily increases the desired time headway of the following vehicle (car-following parameter tau), and also dictates the minimal space headway that has to be maintained between the two vehicles for a pre-determined duration. The execution of the gap creation manoeuvre begins with an adaptation phase, when the desired time headway of the following vehicle is gradually altered using a pre-specified rate. As soon as the desired time

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[1] TraCI is the short term for "Traffic Control Interface". Giving access to a running road traffic simulation, it allows to retrieve values of simulated objects and to manipulate their behaviour "on-line". https://sumo.dlr.de/wiki/TraCI

[2] https://sumo.dlr.de/wiki/TraCI/Vehicle_Value_Retrieval#neighboring_vehicles_.280xbf.29

[3] https://sumo.dlr.de/wiki/TraCI/Change_Vehicle_State#open_gap_.280x16.29

headway is established, it is kept until the ego CAV merges on the target lane. Afterwards, it is reset to its original value. The parameters used in the "open gap" command are presented in **Table 4**.

Table 4. Parameters used in the "open gap" TraCI command.

Parameter Name	**Value**	**Description**
newTimeHeadway	4 s	The vehicle's desired time headway will be changed to the given new value with use of the given change rate.
newSpaceHeadway	15 s	The vehicle is commanded to keep the increased headway for the given duration once its target value is attained.
duration	5 s	The time period in which the time and space headways will be changed to the given new values.
changeRate	0.5	The rate at which the new headways' effectiveness is gradually increased.
maxDecel	1 m/s^2	The maximal value for the deceleration employed to establish the desired new headways.
referenceVehicleID	ID #	The ID of the reference vehicle.

The action steps performed in SUMO for the implementation of the cooperative manoeuvring logic are illustrated in **Figure 3**. Blue colour indicates actions commanded by TraCI, pale orange colour relates to traffic operations determined by SUMO lane change logic, while pale green colour pertains to information returned by TraCI commands.

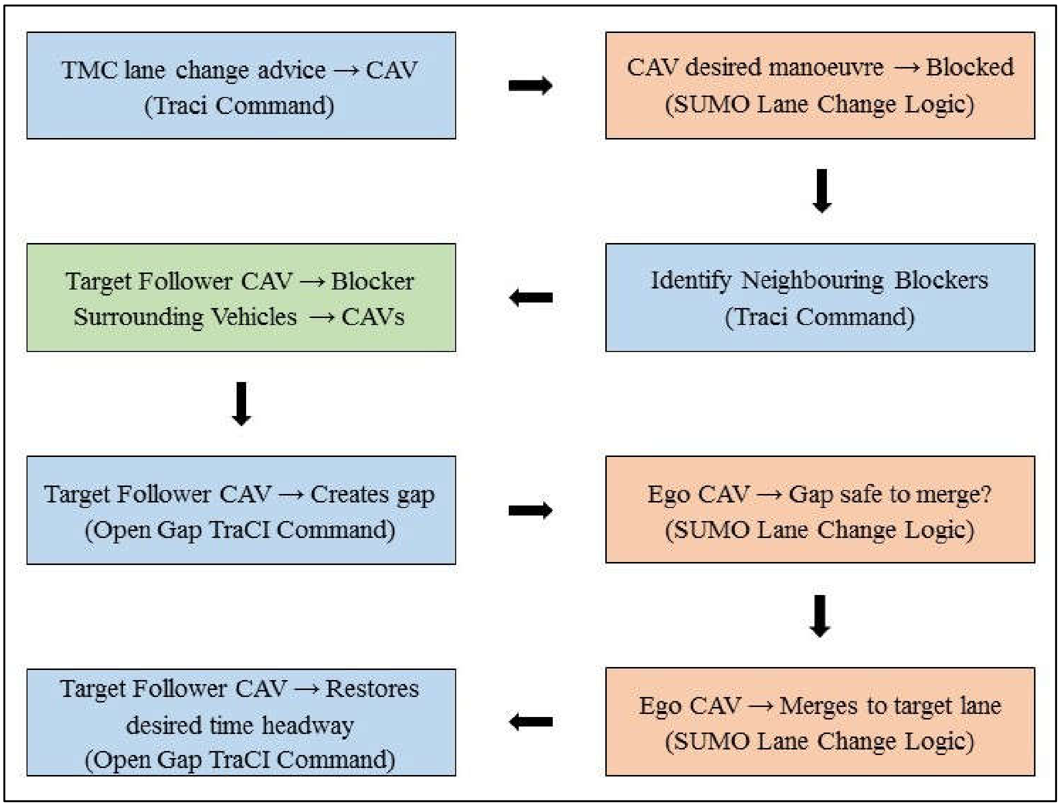

Figure 3. Simulation of cooperative manoeuvring in SUMO.

4.1 Scenario 3.1 Apply traffic separation before motorway merging/diverging

4.1.1 Description of Cooperative Manoeuvring

Highly complex vehicle interactions at motorway merging areas might induce disengagements of driving automation systems (**Figure 4**). The resulting control transitions (system-initiated downward transitions) can yield adverse impacts to safety, traffic efficiency and the environment, especially when drivers are unresponsive to take over requests and thus (C)AVs are forced to execute MRMs. Hence, a traffic separation policy was proposed in Deliverable 4.2 (Maerivoet et al., 2019) that assigns vehicles to designated lanes based on their automated driving capabilities. The means to implement the proposed policy differ according to the vehicle type. Individualized messages (MCMs) are sent to CAVs/CVs from the TMC side, while LVs are informed about the enforced policy through a Variable Message Sign (VMS) that is installed upstream of the traffic separation entry point.

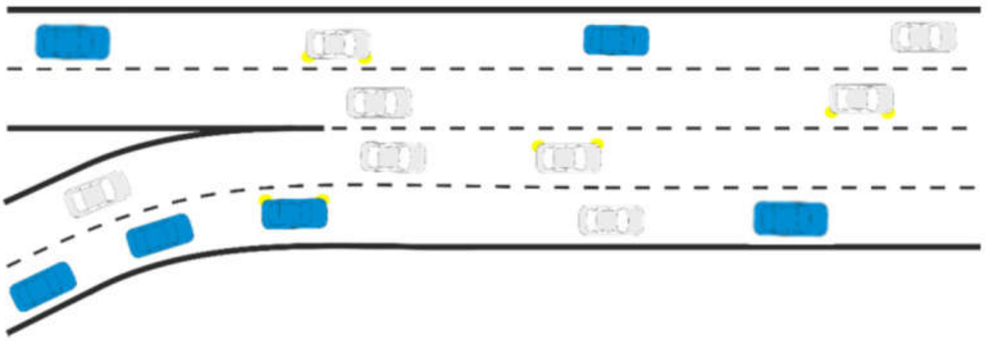

Figure 4. Schematic overview of Scenario 3.1.

The implementation of the traffic separation policy requires the execution of lane change advice from the vehicle side. For example, the TMC constantly knows the driving lane of each CAV when it enters the traffic separation area. If the CAV enters the traffic separation area, but is driving on the non-CAV designated lane the TMC will advise the CAV to change lane. However, the suggested lane change manoeuver might be blocked due to surrounding vehicles. In this case, the cooperative manoeuvring framework presented in Section 3 can be applied to facilitate the CAV desired lane change manoeuver. The actions required for implementing cooperative manoeuvring in SUMO are simulated with the use of the logic and TraCI commands presented in Section 4.

A timeline of possible actions during cooperative manoeuvring in SUMO is illustrated in **Figure 5**. CAVs are depicted in blue colour, CVs in yellow, and LVs in white. Frame (A) shows an ego CAV approaching the entry of the traffic separation area. Its target follower and leader are also CAVs. Once the ego CAV enters the traffic separation area it receives lane change advice from the TMC (yellow turning lights are on in the left CAV side) since the left lane has been assigned to CAVs/CVs (Frame B). However, the ego CAV is blocked by surrounding vehicles and cannot implement the advised lane change manoeuvre. Thus, the TraCI command that retrieves information with respect to neighbouring vehicles is applied and it identifies that the target follower blocks the ego CAV, and that it is a CAV as well. Since the target leader is also a CAV, cooperation between the ego CAV and the target follower CAV is granted (cooperating vehicles in purple colour). Thus, the “open gap” TraCI command is applied and the target follower gradually increases its desired headway with reference to the ego CAV (Frames C – D). When the available gap between the ego CAV and the target follower CAV is considered safe by the ego CAV to merge on the CAV designated lane, the lane change manoeuver begins (Frames E – F). During cooperative manoeuvring, the exchange of information between the cooperating entities relaxes the required safe gaps for lane changing from the ego CAV side. Finally, the ego CAV merges onto the CAV designated lane prior to the exit of the traffic separation area.

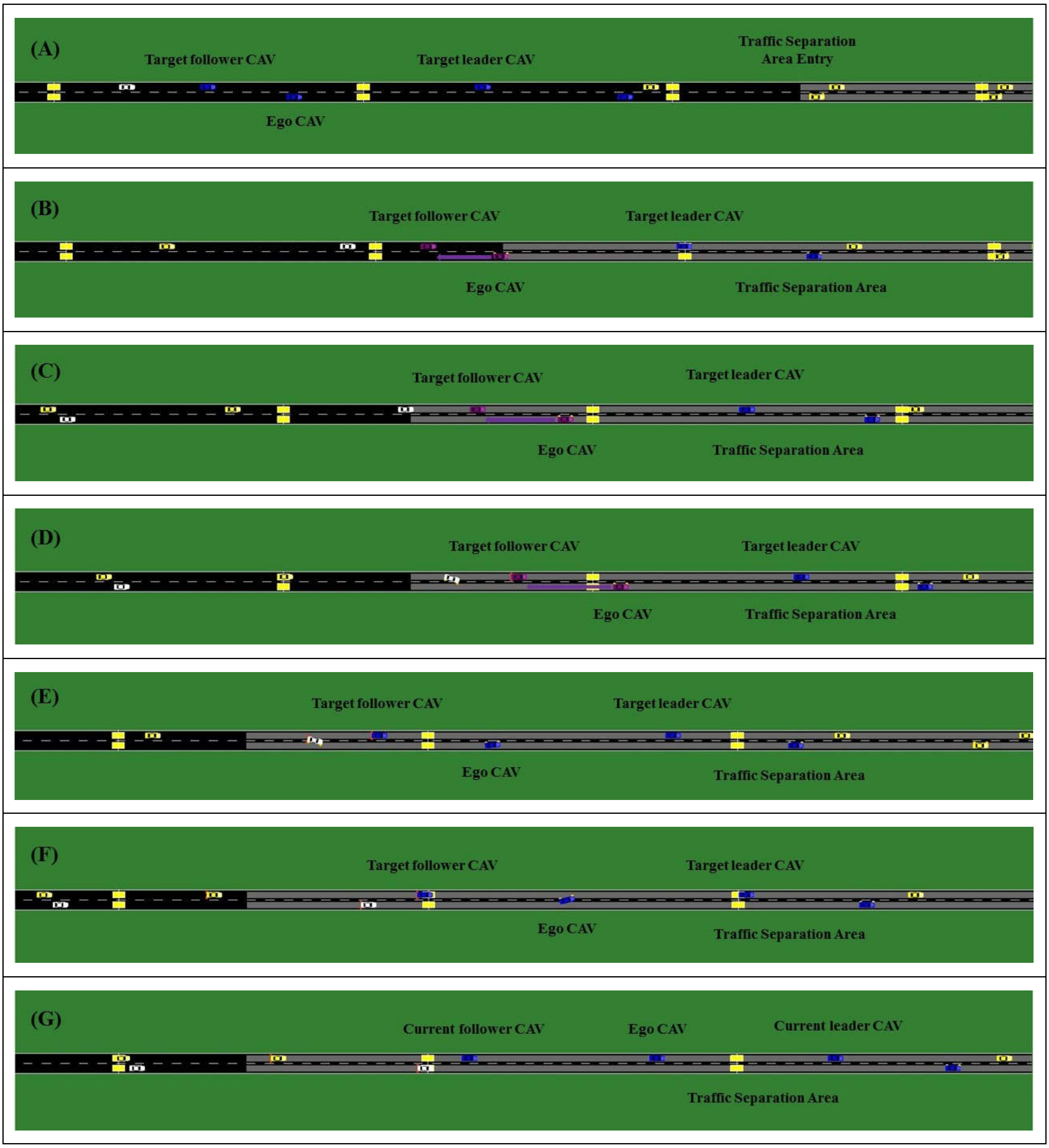

Figure 5. Timeline of cooperative manoeuvring actions in SUMO for Scenario 3.

5 Adaptation of AV and Driver Models

5.1 Integration of AV and Driver Models in iTETRIS

In Deliverable D3.1 (Mintsis et al., 2018), we developed AV and driver models to simulate: a) AV longitudinal and lateral motion, and b) driver behaviour and AV motion during AV disengagements. An Adaptive Cruise Control (ACC) model previously proposed by (Milanés & Shladover, 2014) was adapted and integrated in SUMO to replicate AV longitudinal motion. The default SUMO lane change model (Erdmann, 2014) was parametrized with the use of experimental lane change values provided by Hyundai Motor Europe Technical Center (HMETC) to reflect actual AV lane change behaviour. Finally, a ToC/MRM model was developed to emulate driver behaviour and AV motion in the course of system-initiated downward ToCs.

However, the operation of the latter models is inherently decoupled from connectivity requirements, since V2X communications do not influence the manipulation of AV behaviour in SUMO. On the contrary, adaptation of CAV models for integration in iTETRIS will be required during the 2nd project iteration when Cooperative Adaptive Cruise Control (CACC) will be modelled and simulated both in SUMO and iTETRIS. Since CACC is based on the exchange of Cooperative Awareness Messages (CAMs) between CAVs to facilitate CACC-equipped vehicle's longitudinal motion, and the corresponding message exchange needs to be simulated in iTETRIS, necessary changes will be incorporated into the CAV model to enable high fidelity simulations. The same also applies in the case of cooperative manoeuvring where the message exchange (MCM) is a prerequisite for its implementation and simulation in iTETRIS. Detailed information regarding the adaptation of the AV models (CACC, Cooperative Manoeuvring) so that they become functional in iTETRIS will be provided in the 2nd version of Deliverable D3.2.

5.2 Implications of Real-World Experiments on AV and Driver Models

Up to now only very few driving tests have been done in TransAID, since the first iteration is still on-going in the real-world experiments and feasibility assessments. Nevertheless, there are already a few "lessons learned", which are summarized in the following:

- **Cooperative Lane Change in the light of the MCM definition**

One of the most promising solutions for cooperative lane changes is done in the manoeuvre coordination service (MCS) with its message derivate MCM. Although the MCM is still quite vague in terms of definition, there are already some findings related to it. In the MCM, a vehicle is informing the others about the trajectory it is currently driving on, and – if suitable – about the trajectory it would like to drive on. Other vehicles may react to this desired trajectory by adapting their own trajectory. While most of the test cases explicitly deal with cooperation between single vehicles (e.g. the vehicle who wants to change lane is only cooperating with the target follower), cooperation can be considered in a broader sense, where the ego CAV plans a trajectory affecting several others, which in turn need to react to make this plan feasible. For example, this type of cooperation could involve target leader, target follower, and several other vehicles on other lanes. It is yet undefined if the MCM will include the possibility of multi-agent cooperation at the end, since also IDs for bilateral cooperation are discussed. Therefore, future driver models need to have a flexible definition of cooperation paradigms, in order to cope with future requirements. However, independent of the final message definition, it is quite realistic that cooperation with different agents will be feasible at the end, either by one or by several independent cooperation requests. Therefore, it can be agreed that cooperative lane changes include cooperation of several entities in the TransAID simulations.

- **Human-centred design of cooperative manoeuvring models**

Following real-world AD prototypes and the objective of making them as close as possible to human-driven vehicles in their behaviour, the need arises to implement “user-friendly” cooperative manoeuvring implementations. Considering the need of letting the follower car opening a gap for the merging vehicle, it cannot be assumed that the follower vehicle would open a gap blindly upon any ego-vehicle’s requests. Uncomfortable decelerations must be prevented in this context. For this purpose, it is important to consider the relative time/space with respect to the ego-vehicle from where the following car starts to consider the open gap request. With the objective to provide a “user friendly” open gap manoeuvre to the driver of the following car, it is correct to fix a $maxDecel$ parameter to adopt (here values like 1-2 m/s^2 seem adequate). Then, if the following car is not able, with this deceleration, to open the gap by a given target point (indicated dynamically by the ego-vehicle), the open gap request should be rejected.

- **ToC behaviour**

While it is assumed that ToCs are going to happen in many situations depicted in the defined scenarios, it is questionable if this is a realistic approach. One example is given in **Figure** , where the CAV is stopping in front of the blockage and – according to the definition of Scenario 1.1 – performing a ToC. In real world, this requires a good sensor data interpretation. Just detecting the obstacle ahead will only cause the vehicle to stop, or to do a lane change to the right lane and stop there without ToC. Most likely, it will be the driver initiating the ToC after a critical time point. Nevertheless, the ToC may still happen, in case the vehicle is receiving a DENM indicating that the obstacle is going to remain on the road. This example indicates that transition handling is not very simple and special care needs to be given to each of the modelled transitions, their parameters and the resulting behaviour.

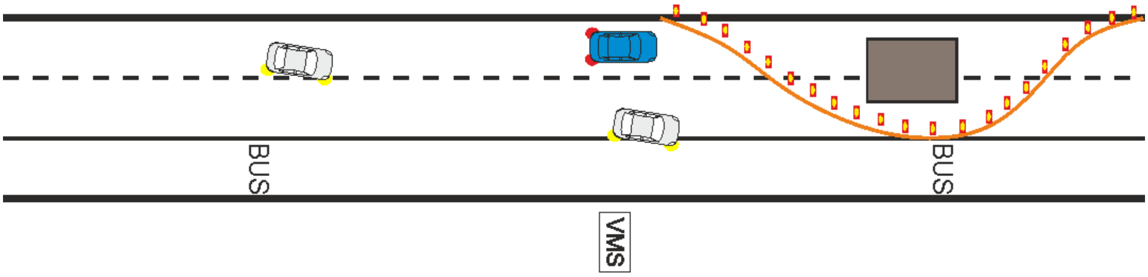

Figure 6. Questionable ToC of a CAV.

- **Model simulation accuracy and sending frequency**

Several parts of vehicle automation software are requiring a fast update of the components and related to this a high triggering frequency. This high frequency is very often stabilizing the movement of the car. While this is true for vehicle automations, this high frequency has a lot of negative implications for vehicle simulations as done in TransAID, where several vehicles (and later on also their communication) are simulated, resulting in already high demands on computer power. On the other hand, doing a vehicle automation simulation only once a second may induce unrealistic braking manoeuvres, which will be much more flattened when simulated in higher frequency. Choosing the correct parameters for stable and realistic simulations is therefore a difficult task that should not be underestimated. This is especially true for communication, where real world tests already showed imperfect behaviour when messages arrive in 1 – second intervals, since this already implies an approximation of future behaviour.

6 Conclusions

In the preceding sections, we presented cooperative manoeuvering in the context of TransAID. A framework was developed to enable cooperative manoeuvering modelling and simulation in the micrcoscipic traffic simulator SUMO. The latter framework encompasses both a centralized and a decentralized cooperative manoeuvring approach. In the centralized approach CAV cooperation is facilitated through the TMC, while in the decentralized one it is directly established between the cooperating CAVs with the use of V2V communications. The triggering conditions for cooperative manoeuvering per traffic management plan that were previously presented in Deliverable D4.2 are also recaped.

Since Deliverable D3.2 explicitly deals with the execution of the cooperative manoeuvering actions in the microcopic simulation environemnt, we introduce newly developed TraCI commands that enable the simulation of coopeartive manoeuvering in SUMO. A TraCI command is capable of identifying the vehicle types of blocking vehicles surrounding a CAV, while the "open-gap" TraCi command adjusts the desired time headway of the target follower CAV with reference to the blocked CAV in order to create a safe gap that will allow the ego CAV to merge onto the desired driving lane. The latter commands are used to simulate cooperative manouevering in the context of Scenario 3 (Apply traffic separation before motorway merging/diverging). Focus is placed explicitly on Scenario 3, since the cooperative manoeuvering mechanism is common among the examined TransAID scenarios.

AV and driver models developed during the 1st project iteration do not require V2X communications to determine vehicle behaviour during simulations. Thus, adaptation of these models is not a prerequisite for integration in the iTETRS simulation platform. This task will be implemented during the 2nd project iteration when CACC and cooperative manoeuvering models will be used to replicate CAV motion. Finally, Section 5.2 highlighted that modelling of future behaviour has to be done carefully, since several details are not yet known and effects of wrongly estimated parameters can be large.

In Deliverable D3.2 we investigated cooperative manoeuvering in the form of gap creation from the target follower CAV to facilitate the ego CAV desired lane change manoeuver. Hence, we applied a manoeuver specific method to implement cooperative maneouvring in SUMO disregarding the potentially negative impacts that a locally coordinated manoeuvre might entail to surrounding traffic. During the 2nd project iteration we are planning to consider more complex CAV interactions (longitudinal and lateral manoeuvres) for the implementation of cooperative manoeuvering. Moreover, we are going to explore the possibility of deploying manouvre-genenric methods for CAV cooperation in future simulation experiments. Finally, focus will be placed on the centralized approach where enhaced perception of the road enviroment allows multi-agent vehicle cooperation that can benefit network-wide traffic efficiency.

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