D3.2

Cooperative maneuvring in the presence of hierarchical traffic management

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■ PU : Public

□ RE : Restricted to a group specified by the consortium (including the Commission Services)

□ CO : Confidential, only for members of the consortium (including the Commission Services)

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Executive Summary

This present document is Deliverable D3.2 entitled "Cooperative manoeuvring in the presence of hierarchical traffic management", which was prepared in the context of the WP3 framework of the TransAID project. The scope of this document encompasses the modelling and simulation of cooperative manoeuvring in the context of the microscopic traffic simulation activities conducted within TransAID. Initially, the state of the art in the domain of cooperative manoeuvring is provided and then two different cooperative manoeuvring frameworks are introduced. The first one is a decentralized framework where cooperative manoeuvring is solely based on vehicle-to-vehicle (V2V) communications, while the second one is a centralized framework that utilizes vehicle-to-anything (V2X) communications. A work zone scenario is used to elaborate on the operation of the centralized approach. The logic for simulating the decentralized approach in the microscopic traffic simulator SUMO is subsequently introduced along with the corresponding functionalities that were developed within SUMO for this purpose. Cooperative manoeuvring is coupled with hierarchical traffic management by explaining how the decentralized approach can be integrated in the traffic management plans that were developed for each use case examined in the context of TransAID. Cooperative manoeuvring is coupled with traffic separation in SUMO and a timeline of cooperative manoeuvring actions in the simulation is presented. Coupling with communications is also addressed. Moreover, adaptations to the driver-vehicle models encompassing communication requirements are proposed to enable integration in iTETRIS. Finally, recommendations for fine-tuning of driver-vehicle models in simulation are provided based on the findings of the real-world prototype experiments.

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, CAVs, automated vehicles (AVs) of different SAE levels, cooperative vehicles (CVs) able to communicate via 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 at TAs in two project iterations. Each project iteration lasts half of the total project duration. During the 1st 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 2nd 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 is increased.

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 V2V communication. The logic and required functions for the implementation of cooperative manoeuvring in SUMO are also presented. Decentralized cooperative manoeuvring is explicitly described in the context of Scenario 3.1 (Apply traffic separation before motorway merging/diverging), while centralized is elaborated in the context of Scenario 4.2 (Safe Spot in Lane of Blockage & Lane Change Assistant). 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 3.1 (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 summarizes the findings of Deliverable D3.2.

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 et al., 2018). However, in general the majority of AVs will only be capable to locally interpret the future intentions of 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 et al., 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 and 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 et al., 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 notion of "desired" and "planned" trajectories was also leveraged by (Wartnaby and Bellan, 2019) to propose a decentralized cooperative collision avoidance algorithm that jointly optimizes trajectories of an ad-hoc group of vehicles. The optimization task is performed based on a protocol that requires no leader and no explicit inter-vehicle agreement and results in robust handling of a wide range of collision scenarios, with no hard limit to the number of cooperating vehicles. (Shen et al., 2018) developed a distributed optimal control algorithm that enables cooperative lane change decision making and longitudinal motion planning among multiple CAVs around highway merge areas. The algorithm's performance was found superior to sequential planning policy and scenarios without lane change based on numerical simulation evaluation. Numerical simulations were also used to demonstrate the efficiency of a parallel optimization algorithm that facilitates centralized cooperative manoeuvring at large scale (Wang et al., 2018). Optimal coordination of CAVs was also investigated by (Zhao and Malikopoulos, 2018) based on a decentralized optimal control framework. The latter framework optimises vehicle trajectory across its entire route and was proven to enhance network performance according to microscopic traffic simulation results. Finally, (Correa et al., 2019b) proposed an extension to the ETSI defined Manoeuvre Coordination Service (MCS) to allow infrastructure support for cooperative manoeuvres using I2V communications.

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) were addressed during the 2nd project iteration, when methods for vehicle cooperation at large scale are explored.

3 Modelling Cooperative Manoeuvering of CAVs

3.1 First Iteration

3.1.1 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). 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**)**.

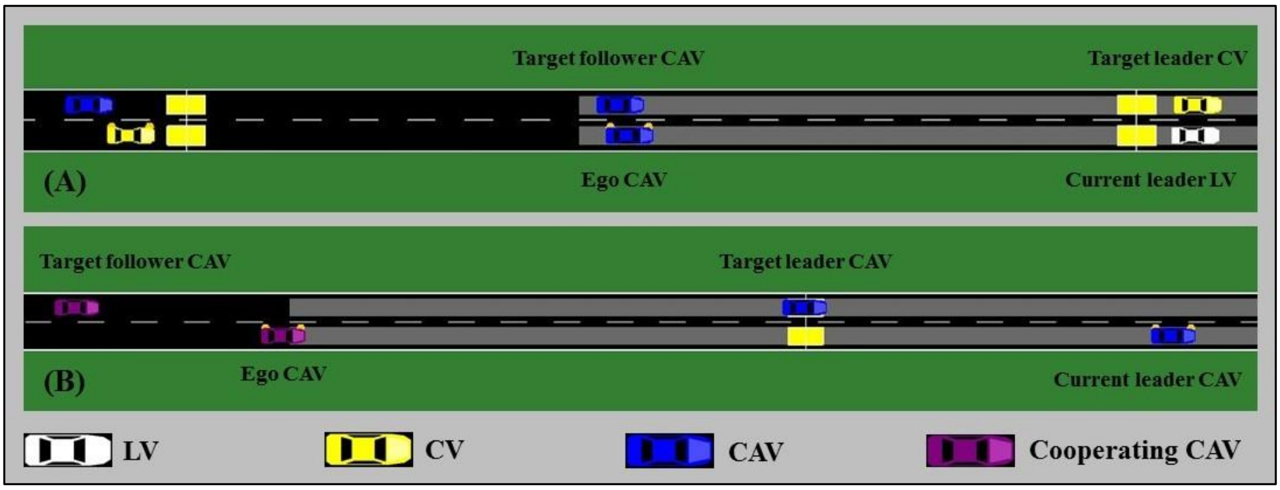

Figure 1. (A) Vehicle cooperation cannot be implemented since every neighbouring ego CAV vehicle is not CAV. (B) Vehicle cooperation is possible since the ego CAV is surrounded by CAVs.

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 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, 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 simulation experiments of the 1st iteration). 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 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 V2X communication range 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 (or aborted in case of imminent threats to traffic safety). 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.

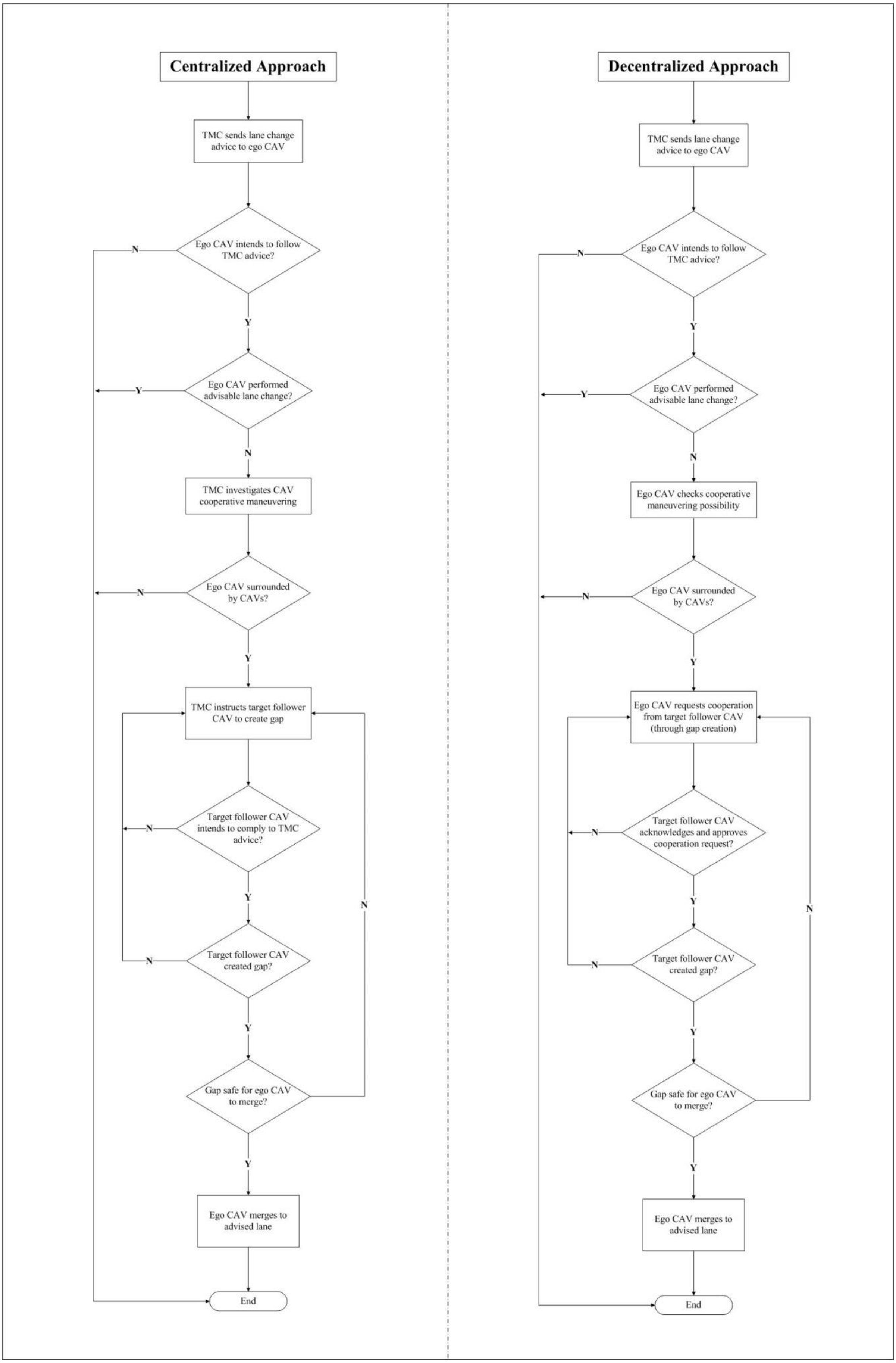

Figure 2. Centralized and decentralized cooperative manoeuvring approaches in TransAID.

3.1.2 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 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 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 for 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 3.1.1, 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 3.1 (taken as reference) in Section 4.1. In the present second version of Deliverable D3.2, we look into complex cooperative manoeuvring cases, which concurrently consider higher vehicle interactions (cf. 3.2.1).

3.1.3 Coupling with Communications

Besides modelling, Deliverable D3.2 deals with the simulation of 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., 2019a). In the latter deliverable, the flow of Manoeuvre Coordination Messages (MCM) is introduced for both the centralized and the decentralized cooperative manoeuvring 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.

3.2 Second Iteration

3.2.1 Centralised Cooperative Manoeuvring Approach

In preceding sections (cf. 3.1.1) we explained how the TMC acts as an intermediary entity in the case of centralised vehicle cooperation to coordinate CAV actions in the context of a cooperative lane change manoeuvres. In the 2nd project iteration we focus on the possibilities provided by centralised cooperative manoeuvring approach to ensure efficiency and safety of cooperative lane changes through enhanced knowledge about surrounding road traffic. Thus, we define a set of risks for cooperative manoeuvring posed by neighbouring vehicles, we introduce mitigation measures for the latter risks considering TMC capabilities in terms of knowledge about prevailing traffic conditions and CAVs' intentions, and finally we propose triggering conditions that warrant the activation of the mitigation measures which enhance traffic safety and efficiency for the entire traffic stream. Table 3 depicts the potential risks, the relevant mitigation measures, as well as the triggering conditions per measure.

Table 3. Cooperative manoeuvring risks – TMC mitigation measures – Triggering Conditions.

No.	Risks	Mitigation Measures	Triggering conditions
1	Following vehicle(s) speeding close to cooperating vehicles	• Abort cooperative manoeuvre if immediate followers are LVs/CVs • Advice safe headways to following vehicles if followers are CAVs	• $s_{fol}^{dif} < s_{critical}$ • $u_{fol}^{dif} < u_{critical}$ • Follower vehicle type?
2	Shockwaves induced to upstream traffic	• Keep lane advice to upstream vehicles • Advice safe headways to following vehicles • Apply mild deceleration rates during cooperative lane changing	• $s_{fol}^{dif} < s_{efficiency}$ • $u_{fol}^{dif} < u_{efficiency}$ • Follower vehicle type?
3	Preceding vehicles decelerating strongly	• Abort cooperative manoeuvre	• $s_{lead}^{dif} < s_{critical}$ • $u_{lead}^{dif} < u_{critical}$

The latter risks, mitigation measures and triggering conditions form the basis for the development of a centralised cooperative manoeuvring algorithm that is shown in Figure 3. Centralised cooperative manoeuvring algorithm.. The algorithm assesses traffic conditions concurrently downstream and upstream of potentially cooperating CAVs in order to provide advice either to nearby traffic or to cooperating CAVs. Safety is valued higher compared to traffic efficiency, and thus safety critical situations can result in termination of vehicle cooperation. The algorithm evaluates headway and speed differences between cooperating CAVs and surrounding vehicles (leaders and followers) to determine the appropriate course of actions.

In specific, potential disruption by surrounding vehicles is examined after a cooperative lane change has been determined as locally feasible (ego CAV is surrounded by CAVs that accepted cooperation request). Initially, the algorithm evaluates if safety critical thresholds with respect to headway and speed differences between cooperating CAVs and neighbouring vehicles (leaders and followers) have been violated. In this case, TMC advises cooperating CAVs to abort cooperative lane changing for safety reasons. Otherwise, headway and speed differences are compared to efficiency critical thresholds. Advice is subsequently provided according to vehicle type of neighbouring vehicles. If

LVs/CVs violate efficiency critical thresholds, TMC instructs cooperative lane change termination since proper LV/CV response to TMC advice cannot be guaranteed (in the case of LVs advice provision is not feasible as well). On the other hand, lane keep and headway advice is communicated to CAVs, so that termination of cooperative lane changing is prevented. If efficiency thresholds are not violated by surrounding traffic cooperative lane changing is executed unimpeded.

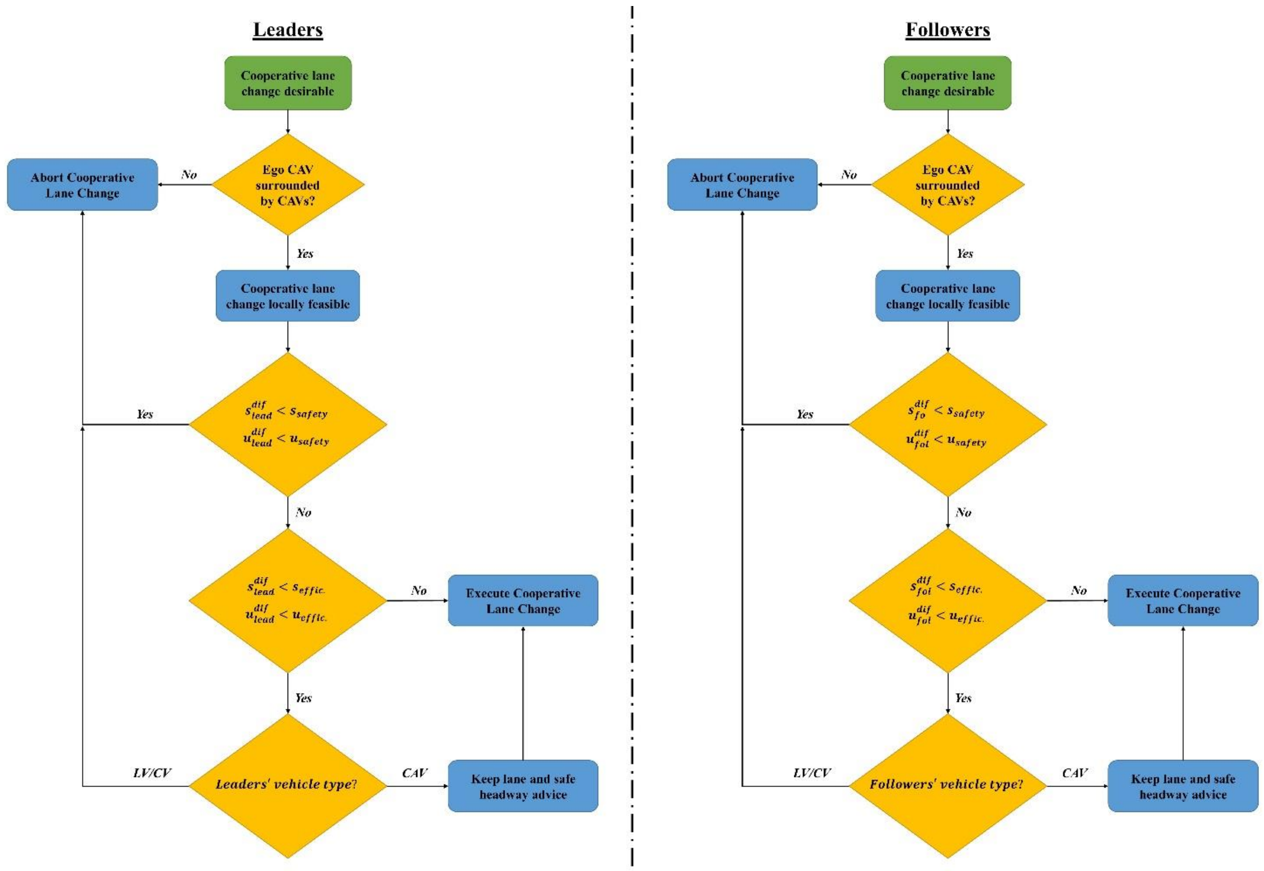

Figure 3. Centralised cooperative manoeuvring algorithm.

In the following we present two specific situations, where surrounding traffic behaviour forces TMC to instruct termination of cooperative lane change manoeuvre to cooperating CAVs. Figure 4 depicts a situation when cooperative lane changing is disrupted by the actions of a preceding CAV. Particularly, cooperation is established between two CAVs that will enable a cooperative lane change (State A). However, a work zone traffic sign enters sensor range of a preceding CAV which decides to decrease speed prior to lane changing in order to cross the work zone without stopping (State B). Nonetheless, the braking manoeuvre disrupts the upstream cooperative lane change since relative headway and speed with the cooperating CAV is lower than the critical predefined values. Therefore, TMC instructs cooperating CAVs to terminate cooperative manoeuvring to prevent safety critical situations (State C). Otherwise, collision risk between braking CAV and cooperating CAV desiring to change lane could be high. Accordingly, a situation when cooperative lane changing is disrupted by a following vehicle speeding unnecessarily is shown in Figure 5. Finally, we stress that selection of safety and efficiency critical thresholds requires significant simulation testing.

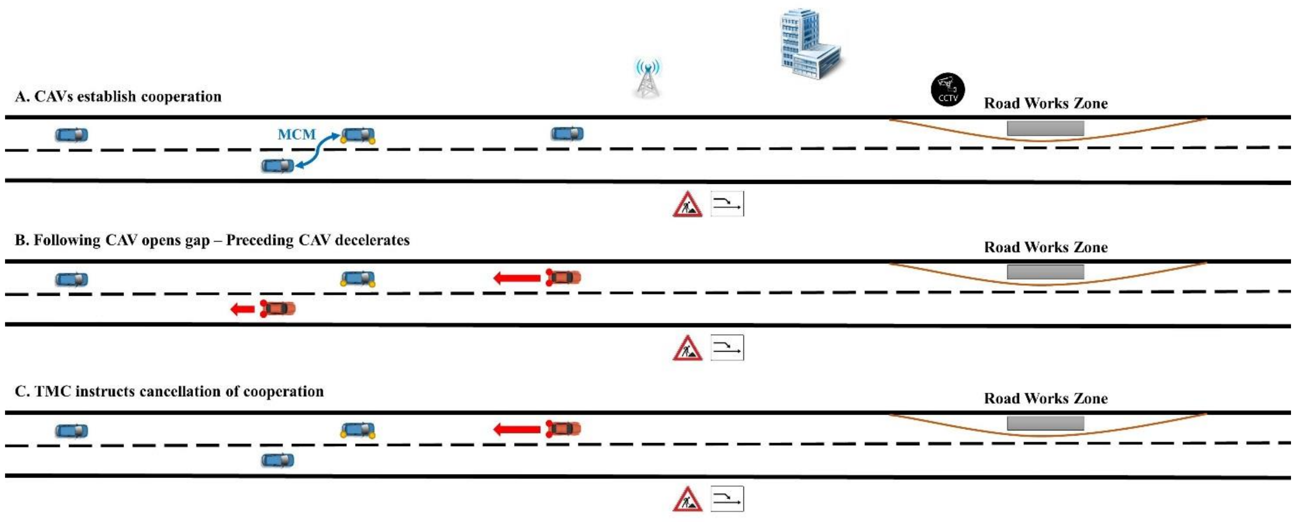

Figure 4. Preceding vehicle disrupts cooperative lane change.

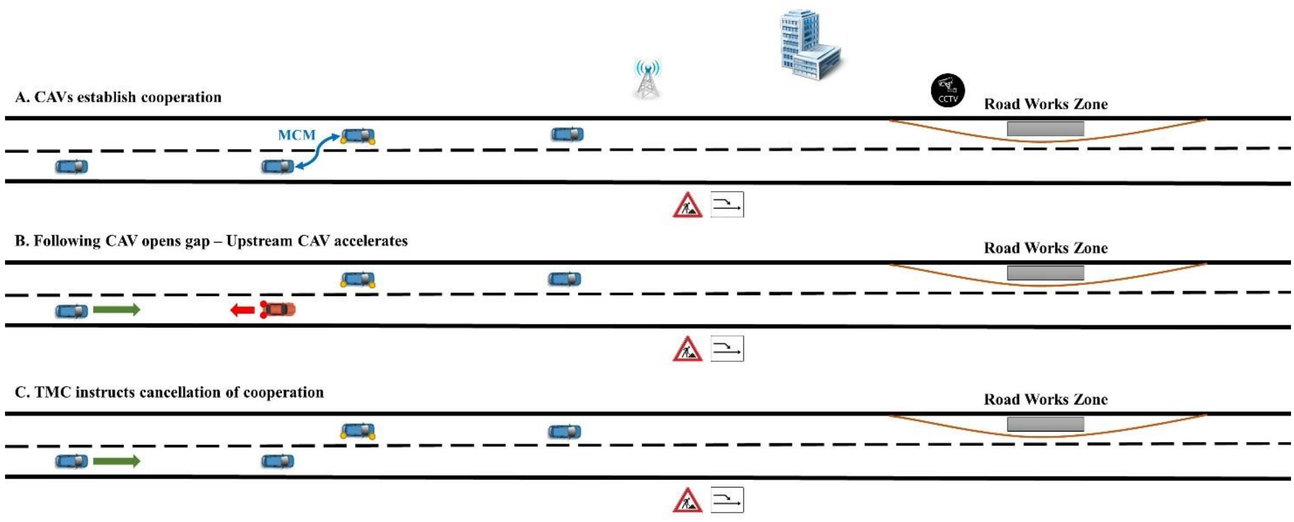

Figure 5. Following vehicle disrupts cooperative lane change.

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 4.

Table 4. 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 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 5.

[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

Table 5. 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 6. 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.

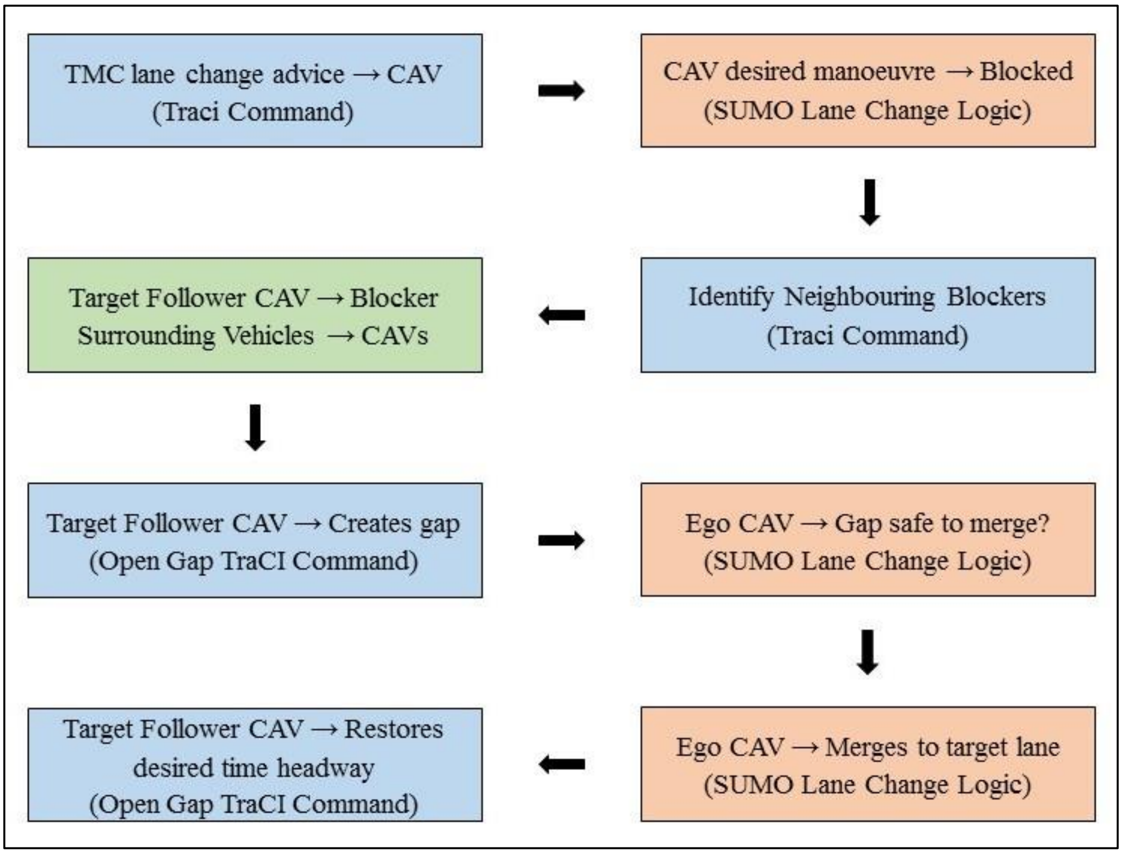

Figure 6. Simulation of cooperative manoeuvring in SUMO.

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 7). 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.

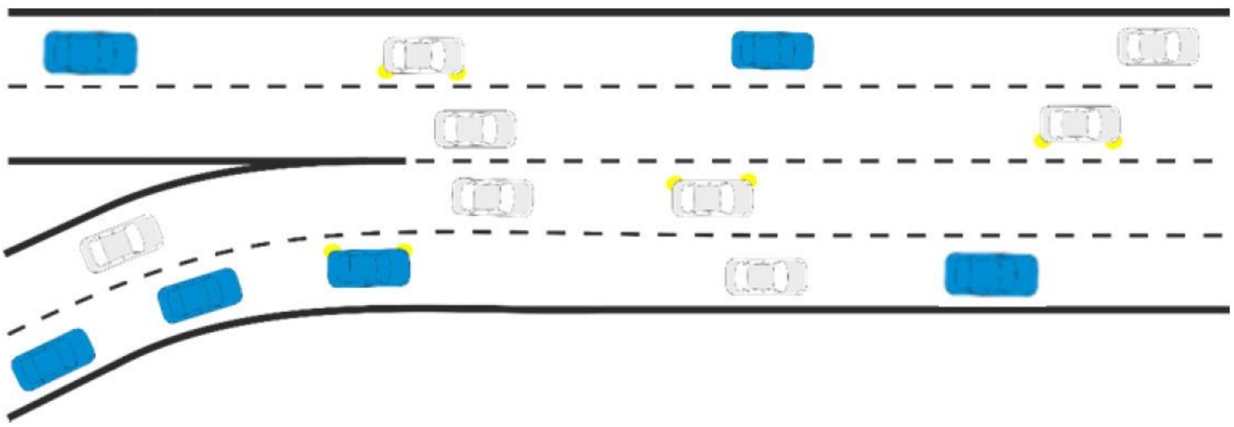

Figure 7. Schematic overview of Scenario 3.1.

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 8. 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 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.

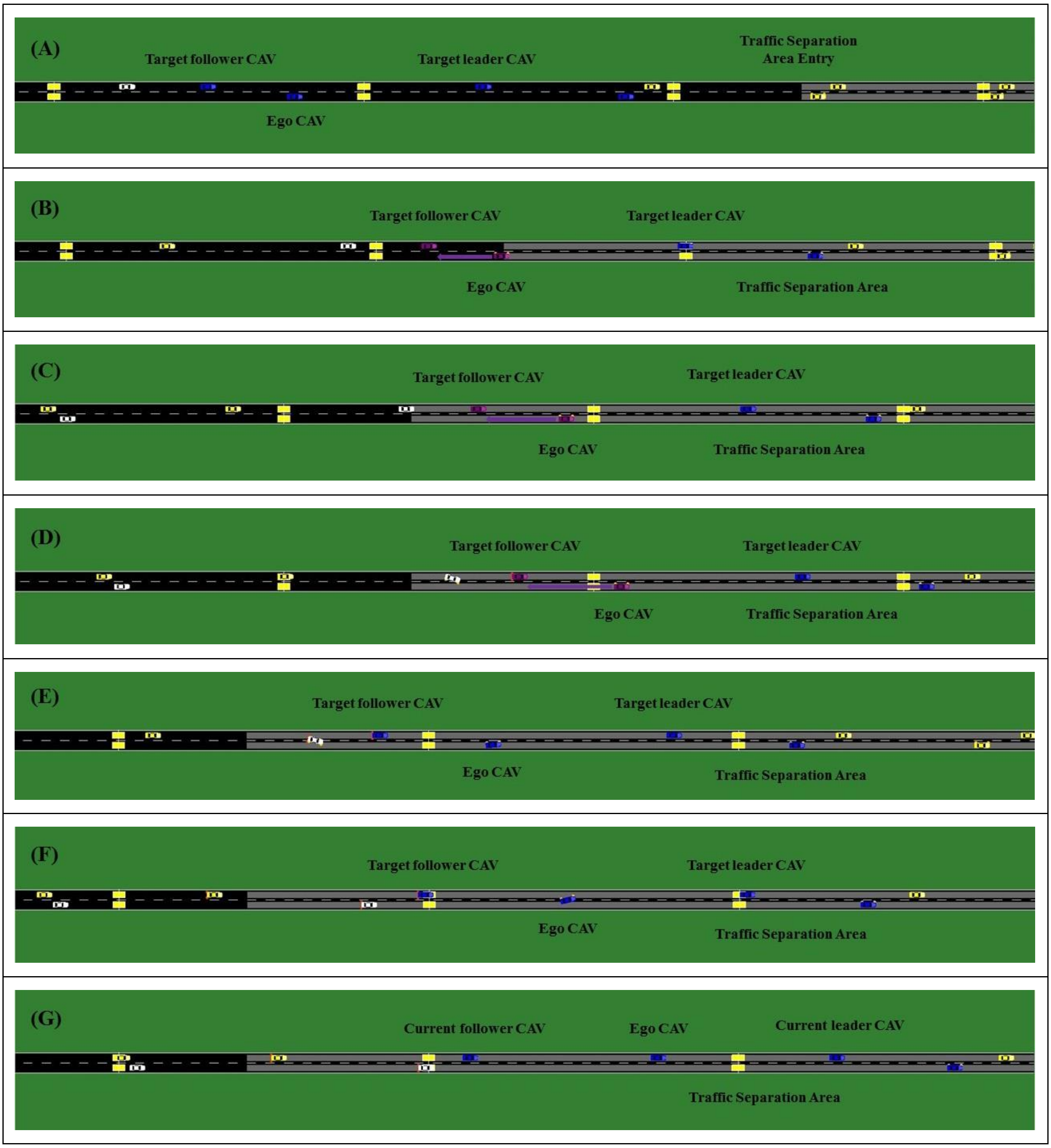

Figure 8. Timeline of cooperative manoeuvring actions upstream of merge area (Scenario 3.1).

5 Adaptation of AV and Driver Models

5.1 First Iteration

5.1.1 Integration of AV and Driver Models in iTETRIS

In Deliverable D3.1 (Mintsis et al., 2019), 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 and 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 data 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.

The operation of the latter models is inherently decoupled from connectivity requirements, since in this case 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 when 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 can be found in 5.2.1.

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

At the time of the 1st project iteration only very few driving tests have been done in TransAID, since the 1st 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 that 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 request. 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 9, 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.

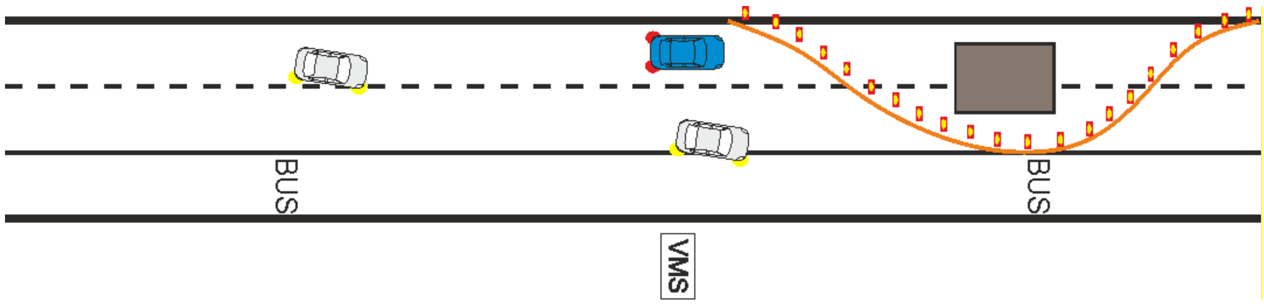

Figure 9. Questionable ToC of a CAV.

- **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.

5.2 Second Iteration

5.2.1 Integration of AV and Driver Models in iTETRIS

A CACC algorithm was integrated in SUMO to replicate car-following behaviour between CVs/CAVs in the 2nd project iteration (Mintsis et al., 2019). As mentioned above, CACC driving relies on the successful exchange of CAMs between CVs/CAVs (V2V connectivity). In the 2nd project iteration we assumed ideal communications for the conduct of baseline and traffic management simulations in SUMO. However, in real world conditions disruption of communications (e.g. latency, package loss, etc.) can lead to disengagement of CACC driving mode. Since realistic communication protocols are considered in the context of iTETRIS simulations, we devise mechanisms which determine CACC activation/deactivation according to communication performance.

Additionally, we developed a distributed approach for cooperative lane changing which was integrated and tested in the SUMO traffic management simulations of the 2nd project iteration. Ideal communications were also assumed in the context of the latter simulations and cooperation requests were granted under any circumstances. Nonetheless, communication errors regarding the exchange of MCMs can disrupt cooperation between vehicles in real traffic conditions. Hence, we develop a mechanism in iTETRIS that assesses successful MCM exchange based on realistic communication protocols to warrant cooperative lane changing among CAVs.

In the following sections we provide generic descriptions of the latter mechanisms. Implementation details, integration in iTETRIS and corresponding simulation results will be presented in Deliverable D6.3.

- **Integration of Cooperative Adaptive Cruise Control (CACC) in iTETRIS**

Figure 10 depicts a driving scenario when communication errors disrupt CACC operation. Initially, two CAVs enter communication range and establish stable CAM exchange (State A). Thus, CACC driving becomes feasible and the following CAV can shorten car-following headway without adversely impacting safety (State B). However, due to communication errors (e.g. latency, package loss, etc.) stable connectivity between the two CAVs is abolished and thus CACC system is deactivated (State C). Eventually, the following CAV reverts back to ACC driving mode and decelerates (or brakes) in order to establish a safe car-following distance in the absence of connectivity.

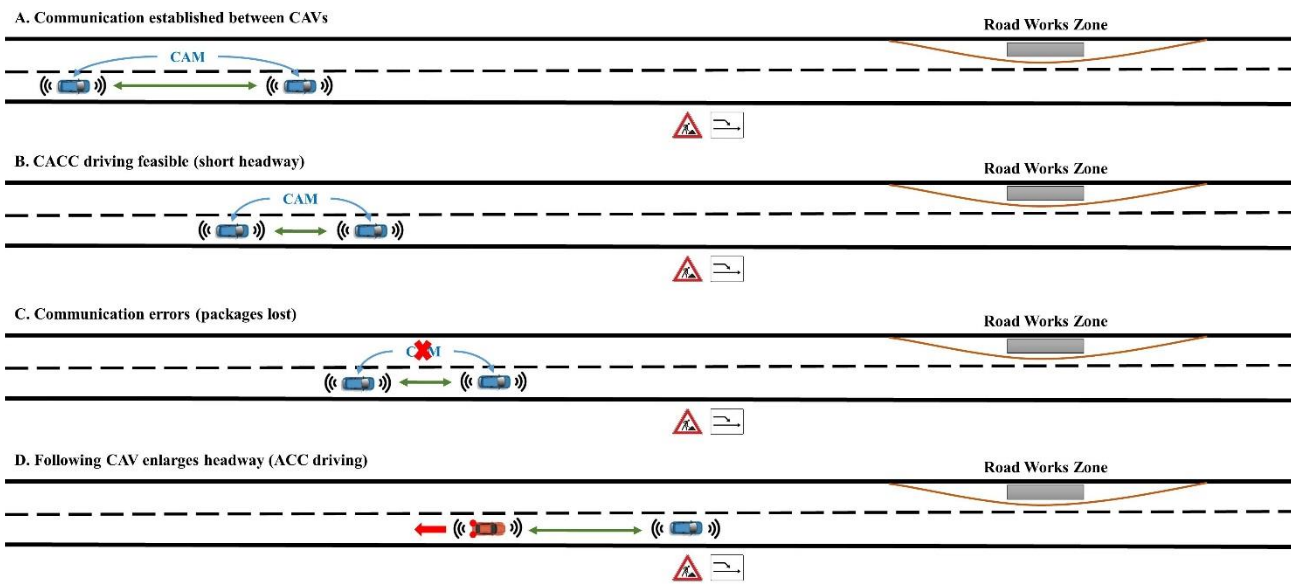

Figure 10. Disruption of CACC driving mode by communication errors.

Our focus is placed on the development of mechanisms which identify communication errors that are critical to the operation of CACC and induce system deactivation. To this end, we adopt two different approaches which can be either applied independently or jointly. According to the first approach, CACC disengagement occurs if CAM update frequency (i.e. time interval until next CAM is received) drops below a critical threshold (timer approach). The second approach is based on the stability of the communication link between CAVs driving in CACC mode. If the percentage of received packages per pre-specified time interval undercuts a critical threshold CACC system disengages. In order to avoid inefficient and frequent system activations/deactivations the proposed mechanisms will be tested and calibrated in iTETRIS. Finally, CACC engagement/disengagement can be applied in iTETRIS by setting vehicle type with the use of a dedicated TraCI command in the Applications module.

- **Integration of Cooperative Lane Changing in iTETRIS**

Figure 11 demonstrates action steps during a cooperative lane change manoeuvre between two CAVs in the context of a work zone scenario. Two CAVs driving on a two-lane road are approaching a work zone in free flow traffic conditions. The preceding CAV drives on the left lane (closed downstream due to road works), while the following CAV drives on the open right lane (State A). When the work zone traffic sign enters field of view of the preceding CAV, lane change feasibility for strategic reasons is assessed according to surrounding traffic conditions. Since the preceding CAV is blocked by the following CAV, manoeuvre coordination is requested by the preceding CAV in the form of gap creation through the transmission of MCM (State B). The following CAV acknowledges the cooperation request by transmitting a relevant MCM (State C), and begins to create a gap (increased headway) with reference to the preceding CAV (State D). Once a safe gap for lane changing is created, the preceding CAV moves to the open right lane (State

E), and subsequently cooperation is concluded when both vehicles can pass unimpeded the work zone (State F).

In order to replicate realistic communications in cooperative lane change scenarios, MCM transmission is modelled on the Application side of iTETRIS. A scheduler of MCM messages is developed that sends cooperation requests when lane change intention is determined by ego CAV and surrounding CAVs block the imminent manoeuvre. Successful MCM transmission (i.e. MCM has been correctly received at the side of the addressed car) is determined by the ns-3 component of iTETRIS. In the context of the iTETRIS simulation experiments we assume that cooperation request is always granted by the following vehicle which opens gap with reference to the ego CAV. The ego CAV explicitly implements the cooperative lane change manoeuvre upon acknowledgement reception (MCM) by the following CAV. Even if the following CAV generates the necessary safe gap to allow the ego CAV to change lane, the latter one will not execute the lane change manoeuvre in iTETRIS unless cooperation acknowledgement has been received (since MCMs are periodic messages and the execution of cooperative manoeuvring is pending till the MCM is retransmitted and received). The structure of the MCM message is adapted accordingly so as to allow the aforementioned operation in iTETRIS.

Another aspect of cooperative lane changing that requires adaptation in iTETRIS simulations pertains to knowledge about surrounding ego CAV environment. In SUMO we assumed perfect knowledge (i.e. vehicle types, position, speed, lane change blockers etc.) about vehicles surrounding ego CAV. On the other hand, knowledge about vehicle environment in iTETRIS should be retrieved from message information (CAM, CPM), sensor/camera data, and data fusion on the infrastructure side. Thus, an additional mechanism is developed in the Application module that can extrapolate information about vehicle environment through the various sources mentioned above. A comprehensive description of the latter mechanism will be also provided in Deliverable D6.3.

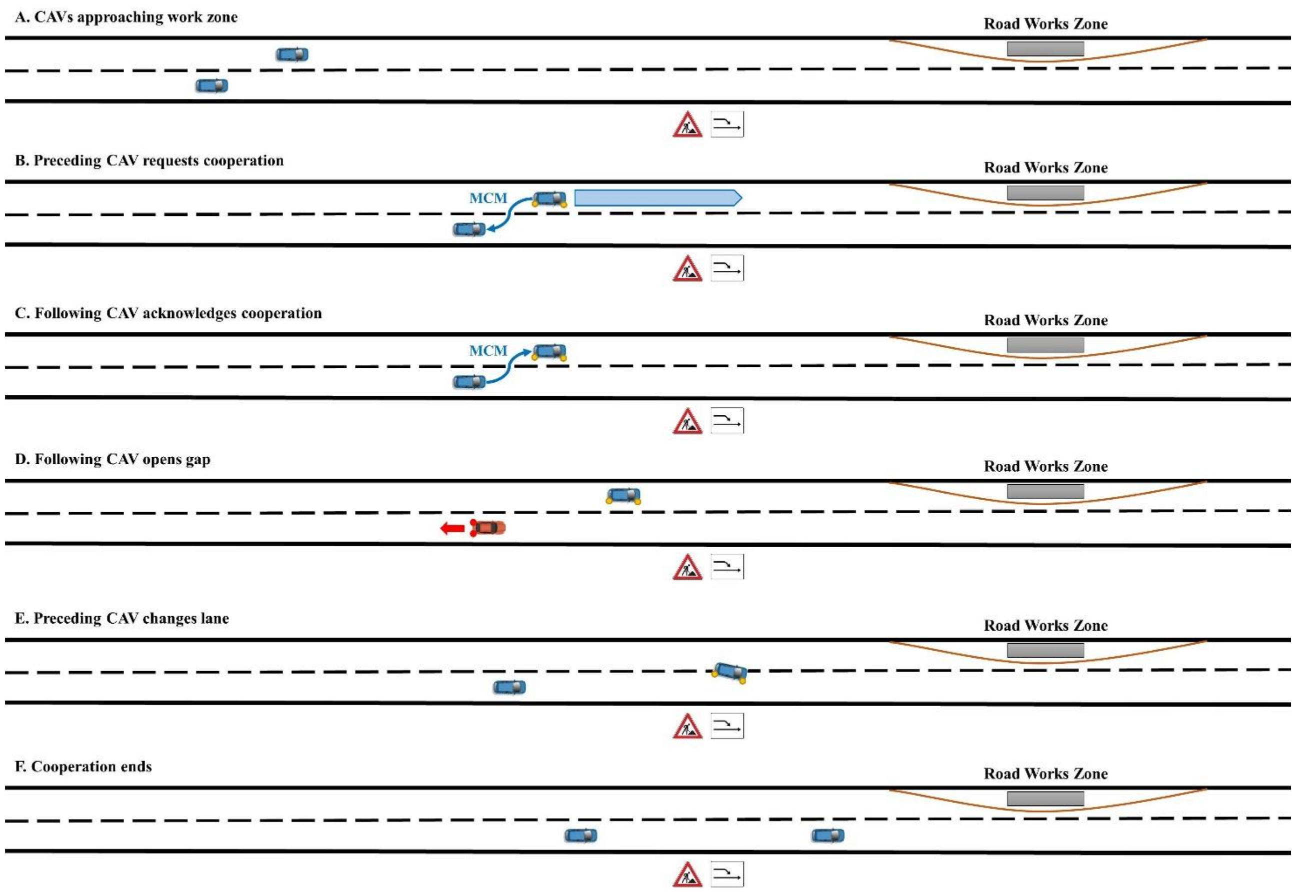

Figure 11. Distributed approach for cooperative lane changing in work zone scenario.

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

Up to now the driving tests of the first iteration have been concluded and the driving tests of the second iteration have just started. Therefore, a list of "lessons learned" is basically available, but needs to be updated later on, which will be done in the final Deliverable D7.2 of WP7. Nevertheless, the already known "lessons learned" are summarized in the following:

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

As identified in the 1st iteration, the MCM is the chosen V2X message for cooperative lane changes in TransAID. The message offers fields for sharing the currently planned and the desired trajectory. One difficulty in this message (current state, see D5.1 for details) resides in the implicit acknowledgements when vehicles are cooperating: Vehicles share their desired behaviour, and a vehicle receiving this information can acknowledge by simply adapting its own planned trajectory and sending out this change. While in theory this behaviour is sufficient and very flexibly usable for diverse situations, it may lead to uncooperative or oscillating behaviour in reality.

One example for this is when safety margins are treated differently in cooperative lane change situations, e.g. when one vehicle provides a desired trajectory for changing lane, while the vehicle on the other lane receives it and answers with a changed planned trajectory. When this planned trajectory includes a minimum distance to the lane changing vehicle, but is too low for the lane changing vehicle, there is basically an acknowledgement which does not lead to a successful lane change and will simply block the procedure. In order to cope with this in reality, additional fields including minimum distances for successful acknowledgements have been included in the MCM (Correa et al., 2019c).

Nevertheless, it should be mentioned that other cooperation techniques exist as well (e.g. dealing with explicit reservation of areas and explicit acknowledgments). One example for this is the STRP, developed in the EU project UnCoVerCPS (Heß et al., 2019), which is designed for V2V cooperation only. Through the explicit reservation and the explicit acknowledgements, the STRP offers guarantees for vehicle automations which cannot be reached by implicit acknowledgements.

Another issue is that the calculation of desired trajectories includes the necessity for the vehicle automation to not only calculate the currently planned behaviour, but also other options. It is questionable if there is only one other option or desire, or if not even more trajectories need to be shared (e.g. MRMs).

Furthermore, a set of parameters is needed for the exact calculation of the trajectories, which are currently not shared in the MCM. Therefore, only trajectories can be part of the negotiation, and not the parameters. This may lead to non-optimal behaviour, as a vehicle can only express one desire in the current MCM, and therefore only one lane change trajectory which is optimal for the vehicle itself, but probably not for the others. Other vehicles may just accept or deny this trajectory, probably resulting in sub-optimal braking behaviour, while the lane changing vehicle could in theory also change one parameter to get better results for all. Centralized approaches could probably help, but the MCM at current stage is also not coping with parameters.

Altogether, modelling and simulation of cooperative lane changes has several new parameters which need to be taken into account, but are currently still under discussion and investigation in the community.

- **Cooperative Lane Change in a centralized way**

In addition to the MCM related discussion, also the centralized procedure needs to be reflected from a real-world perspective. In order to have a stable approach to various coordinated lane changes, infrastructure needs to have a very detailed view on the vehicles on the road. As long as most vehicles are not providing their position and their planned behaviour, it is very difficult to get this view. Sensors need to be installed which are able to track vehicle movements and estimate future vehicle movements, e.g. by also acquiring prescient lane-change indications, like indicator lights, which need to be detected.

The infrastructure also needs additional data like accelerations and current speeds from all obstacles, to be able to calculate optimal behaviour for all road users. Currently, there is no solution for this available on stock. TransAID is working on those solutions, but it will take further investigations beyond the project scope to bring those to the market.

Nevertheless, it should be mentioned that the lack of jittered real life data may affect the simulation results, esp. for lane change advice following a centralized approach. The availability of CAVs and to some extend also CVs will dramatically improve the situation.

- **Implementation of MRMs when benefiting from infrastructure advices**

Right before the conclusion of this deliverable, driving tests have been conducted to experiment the real-world feasibility of I2V assisted ToC. In particular, the road infrastructure has been used to advise a CAV about a specific time and place to trigger a ToC before a non-AD zone. In particular, the road infrastructure knows the start of the non-AD area along with the presence and position of possible safe spots where the CAV can stop in case of MRM. The points for triggering ToR are suggested such that in the worst case the CAV is instructed to drive to a safe spot in MRM. In this case, two alternative approaches have been experimented when the CAV executes the MRM. In the first one, the CAV immediately slows down to a "conservative" speed of 20 km/h and drives at this speed till reaching the safe spot. In the second approach, the CAV keeps its current speed and decelerates right before reaching the safe spot. In both cases, the CAV drives initially at a moderate speed of 60 km/h, and decelerates with an average rate of 0.5 m/s2 to reach the speed of 20 km/h which allows a user-friendly lane change and stop at the safe spot. These real-world validations, aimed at deriving insights on TransAID solutions' feasibility from the functionality, but also user-friendliness point of view, can provide important inputs for modelling or MRM implementation solutions. Yet, it is object of debate which approach is better to follow when a CAV is advised to drive to a safe spot. From one hand, decelerating immediately to a lower speed can help the CAV to rapidly reach a "minimum risk" status and possibly stop at closer safe spots before reaching that suggested by the infrastructure. Nevertheless, having a CAV driving at lower speed can be a risk for other faster traffic participants. From the other hand, keeping the current speed before reaching the safe spot can decrease this risk, but might further endanger the CAVs passengers, as the CAV is in MRM and the driver can probably not respond for bringing the vehicle in a safe state before reaching the safe spot.

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 3.1 (Apply traffic separation before motorway merging/diverging). Focus is placed explicitly on Scenario 4.2 (Safe Spot in Lane of Blockage & Lane Change Assistant) to elaborate on the operation of the centralized cooperative manoeuvering aproach.

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. However in the 2nd project iteration vehicle models based on communication capabilities (CACC and cooperative manoeuvering) were developed that require adaptations for integration in iTETRIS. The propposed mechanims that enable the latter integration in iTETRIS are described in 5.2.2. Implementation of the mechaninsm in iTETRIS and execution of relevant simulations that encompass CACC and cooperative manoeuvering will take place in the context of WP6. Finally, Sections 5.1.2 and 5.2.2 highlighted that modelling of future behaviour has to be done carefully, since several details (e.g. actual vehicle behaviour during ToC, impacts of human-centered design and MCM definition on cooperative lane changing, preffered MRM strategies in the presence of infrastructure assistance) are not yet known and effects of wrongly estimated parameters can be large.

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