



D8.2

Meta-analysis of the results

Project Acronym	TransAID	
Project Title	Transition Areas for Infrastructure-Assisted Driving	
Project Number	Horizon 2020 ART-05-2016 – GA Nr 723390	
Work Package	WP8 Guideline and Roadmap	
Lead Beneficiary	MAP traffic management (MAP)	
Editor / Main Author	Anton Wijbenga	MAP
Reviewers	Miguel Sepulcre Ribes and Javier Gozalvez Sempere	UMH
Dissemination Level	PU	
Contractual Delivery Date	M40 (Dec20)	
Actual Delivery Date	M40 (Dec20)	
Version	v1.0	



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 723390.

Document revision history

Version	Date	Comments
v0.1	01/10/2020	Document structure
v0.2	25/11/2020	Incorporated internal revisions
v0.3	08/12/2020	CERTH, TML and UMH addition, revision and comments
v0.4	14/12/2020	DLR addition, revision, restructure
v0.5	15/12/2020	Minor revisions, glossary, references and executive summary
v0.6	16/12/2020	Minor revisions by DYN
v0.7	17/12/2020	Additional input from HYU processed
v0.8	22/12/2020	Final review by UMH
v0.9	22/12/2020	Preparation of submission ready version by MAPtm
v1.0	30/12/2020	Finalization by DLR

Editor / Main author

Anton Wijbenga (MAP)

List of contributors

Jaap Vreeswijk (MAP)

Evangelos Mintsis (CERTH)

Michele Rondinone (HMTEC)

Miguel Sepulcre (UMH)

Javier Gozalvez (UMH)

Gokulnath Thandavarayan (UMH)

Sven Maerivoet (TML)

Kristof Carlier (TML)

Péter Pápics (TML)

Stef Tourwé (TML)

Bart Ons (TML)

Julian Schindler (DLR)

Matthias Schwambom (DLR)

List of reviewers

Miguel Sepulcre Ribes (UMH)

Javier Gozalvez Sempere (UMH)

Dissemination level:

■ 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)

Table of contents

Document revision history	2
Table of contents	4
Executive summary.....	6
1 Introduction.....	9
1.1 About TransAID.....	9
1.2 Purpose of this document: the meta-analysis	10
1.3 Structure of this document	10
1.4 Glossary.....	10
1.4.1 ODD	13
1.4.2 ISAD	13
2 Summary of the results	15
2.1 The assessment of vehicle automation	15
2.1.1 Discussion	16
2.2 Enhanced traffic management measures	17
2.2.1 Traffic management framework.....	17
2.2.2 Assessment of traffic measures in Transition Areas.....	18
2.2.3 Discussion	21
2.3 Communication at Transition Areas.....	23
2.3.1 V2X communications	23
2.3.2 Communication to non-V2X road users	27
2.4 Assessment of the traffic management procedures	30
2.4.1 Discussion	31
2.5 Real-world implementation.....	32
2.5.1 Discussion	35
3 Gap analysis and recommendations	37
3.1 Behaviour of automated vehicles	37
3.2 Traffic management	37
3.3 Capabilities of V2X.....	38
3.4 Non-V2X communications.....	38
3.5 Real-world implementation.....	39
4 Lessons learned.....	41
4.1 Behaviour of automated vehicles	41
4.2 Communications.....	41
4.2.1 Use case specific V2X communication aspects	42

4.3	Real-world implementation.....	43
4.4	The overall process of the project	44
5	Link to other projects	46
5.1	Related to automated vehicle behaviour	46
5.2	Related to traffic management	47
5.3	Related to V2X communication	47
5.4	Related to HMI and communication to unequipped vehicles	48
5.5	Related to coupling traffic and V2X communication simulation.....	48
5.6	Related to real-world prototyping	48
6	Conclusions.....	50
7	References.....	55
7.1	TransAID documents	55
7.2	External references	56

Executive summary

The TransAID project defines, develops and evaluates traffic management measures based on V2X equipped road infrastructure, primarily via simulations, to eliminate or mitigate the negative effects of Transition of Control (ToC) along Transition Areas in future mixed traffic scenarios where automated, cooperative, and conventional vehicles will coexist. This document aggregates, integrates, and analyses the results of the TransAID work packages. For each aspect of TransAID the major findings are presented and discussed.

As a basis for the simulation studies several vehicle models were implemented successfully to create the right behaviour for lane changing (including cooperative versions), car following (including (C)ACC) and ToC/MRM algorithms. These models were created using a solid theoretical background, however, the availability of real-world data for input and calibration was very limited.

From the baseline simulation runs we found that ToCs do not significantly disrupt traffic flow performance unless CAVs establish increased car-following headways during the ToC preparation phase. Disruptions escalate in case of CACC driving, increased share of CAVs in the fleet mix, and the occurrence of multiple ToCs within a narrow temporal window and spatial domain. Furthermore, in the case that a ToC is unsuccessful or not possible, unmanaged MRMs (taking place in lane and not being guided towards safe spots) can induce significant traffic disruption as well. On the other hand, simulation results indicated that cooperative lane changes minimize the frequency of ToC/MRM and their consequent adverse impacts on traffic flow operations. The benefits of cooperative lane changing are amplified with increasing share of CAVs and especially upstream of lane drop locations.

Building upon the vehicle models, simulations and the defined use cases, specific traffic measures were developed to mitigate the effects of ToC events in transition areas. The traffic measures were implemented to study their effectiveness. Specifically, for each of the selected use cases the effects of the TransAID measures are evaluated regarding emissions, safety and efficiency.

There is a trade-off between traffic safety versus traffic efficiency (as measured via throughput and travel times). It is often inherently difficult or even impossible to optimise both in the same context. Hence, typically a policy choice needs to be made, as to which of the two will have to be prioritised. Otherwise, results either improved or remained similar for all use cases and KPIs, with the exception of use case 3.1 (see Section 2.2.2 for details and Table 1 at the end of Chapter 6).

All use cases have in common that a reduction of MRMs is possible by providing infrastructure advice. Such advice, and the availability of safe spots, clearly reduces the number of stopped vehicles blocking the road.

There is also a heavy dependence of the results on the mixture of vehicle types, in addition to the observation that less efficient traffic management performance is obtained for a higher LOS. The latter is in part logical, as for higher LOS there is more prominent congestion and the physical limits of the infrastructure remain a hard obstacle. By itself this is not a problem for TransAID, as the focus of the traffic management schemes is to prevent/postpone traffic breakdowns before they occur.

While implementing and testing the traffic measures TransAID also identified or created the needed message sets and protocols to implement the measures using V2X communications. To that end, no new message sets were needed, but (minor) extensions to CAM, DENM, MCM and MAPEM were necessary. Especially MCM from the Manoeuvre Coordination Service (MCS) is key to multiple types of use case. Therefore, it is necessary to define a MCS that is valid for all types of scenarios. Aligned with the work of ETSI and by actively contributing, TransAID has proposed a MCS where the infrastructure takes an active role to facilitate the manoeuvres of vehicles and to increase the overall traffic flow and safety.

The traffic management measures designed in TransAID also require that CAVs and road infrastructure units have an accurate perception of the environment. In addition to the MCS, TransAID has contributed to the evaluation and evolution of ETSI's Collective Perception Service (CPS) for cooperative perception. We have demonstrated that cooperative perception can improve CAVs perception capabilities when the trade-off between the perception capabilities and communications performance is balanced. Furthermore, the reliability of V2X communications has been addressed in TransAID using different and complementary techniques: compression, congestion control and acknowledgements.

Besides the V2X communication, the communication to unequipped vehicles was of importance and consisted of two parts. On the one hand, infrastructure needs to inform unequipped vehicles about issues on the road. On the other, automated vehicles themselves should provide information about their actual state to their surroundings, to avoid negative impacts.

With regards to the infrastructure information, it needs to be mentioned that visual information on signs, variable or static, will never be as precise as V2X communication could be, esp. when looking to individual advices. Nevertheless, infrastructure can provide valuable information also to unequipped vehicles by signage, e.g., in terms of speed limits, distance (gap) advice or dynamic lane assignments. It will be required to create additional road signs dealing with automated vehicles, at least showing that, e.g., an area is prohibited for automated vehicles or an area where only automated vehicles are allowed.

Regarding signals from automated vehicles, TransAID's solution of having LED light strips at the back of AVs will be beneficial in any case, but the exact content of such lights needs to be defined by performing more detailed analyses of such components. This goes to all external and dynamic HMI components of automated vehicles. In this light, it will be crucial to have an intuitive way of understanding the automation related additional information. One key question in this area is if driving with enabled automation should be indicated by an additional external light, and if so, where should this light be and what colour?

Combining the work on the traffic measures and communications, the iTETRIS framework was used to evaluate the selected use cases while deploying the traffic measures using V2X. The goal was to see if the V2X communications impacted the effectiveness of the measures in any way.

After adding V2X, the simulation results for the project's first and second iteration use cases showed very similar results to the previous evaluation. All traffic measures were found robust enough to show the same results as with ideal V2X, even in light of increased traffic demand and thus more V2X enabled vehicles. There were some minor differences between the realistic V2X and ideal V2X implementations, but those could be traced back to easily fixed technical aspects (see Section 2.4 for details).

As a final step in our use case assessment, the feasibility of measures and communications introduced were implemented in real-world demonstrators. The real-world implementation was done by performing three different feasibility assessments. Two of them have been performed on test tracks in Germany, and one on public roads in The Netherlands.

On the test tracks, several detailed tests of all scenarios have been performed, revealing that all traffic management measures could be successfully integrated and applied to automated vehicles in all use cases and scenarios. This includes the successful setup of the RSI and the automated vehicles. It has to be mentioned, though, that the implementation was done in a prototypic way.

The development of related series products would require much more testing under real world conditions, which will be challenging at the current time since no highly automated vehicles are present on the roads. Nevertheless, it is very important to start the investigations at present times. As already described in Section 3.3, standardisation of messages is happening already now, and it was

very important to include the role of the infrastructure at this stage. The detailed results of the real-world implementations per use case can be found in Section 2.5.

In addition to the design and technical implementation of traffic measures in simulation and the real-world, TransAID gained some insights on issues of a less technical nature. For example, it was determined a close collaboration between OEMs and (N)RAs would be beneficial in the identification and managing of TAs. To facilitate such a collaboration TransAID proposes a traffic management framework in the form of an intermediary service provider, acting as a trusted (and possibly mandated) third party. The framework allows TransAID to be scaled up and generalised. We approached this from both a technical and a business-oriented perspective. For TransAID to become part of a complete traffic management system, we focused on the technical side on how to detect transition areas, select (and possibly combine) services, and then detect when they are most appropriately timed for deployment. To this end, detection can be done via the infrastructure (e.g. road sensors or even digital communication infrastructure), via the OEMs, or by comparing an infrastructure's newly-defined ISAD level (Infrastructure Support levels for Automated Driving; see Section 1.4.2) to the operational design domain (ODD, see Section 1.4.1) of the vehicle.

Considering the mentioned technical challenges (detecting TAs, selecting services, and timing their deployment), the intermediary service bridges all these parties in such a way that the detection of TAs is performed in a centralised way, and OEMs and (national) road authorities ((N)RAs) have a single point of contact for providing and receiving information about TAs.

Another point where OEMs and (national) authorities could collaborate, is the legislation related to automated driving since an important gap in current modelling and legalisation is how (C)AVs would/should react when (given) advice and/or actions conflict with traffic laws. With the real-time coordinated instructions of a TMC, (C)AVs should drive adequately during their journeys. However, it is necessary to concern to what extent such instructions should/can be made, especially when considering legal issues. In addition, legal aspects like the definition of special signage for automated vehicles and their handling also need to be considered, as those aspects will take time. This also means signage at the roadside, including VMS content, and signage from automated vehicles to surrounding traffic.

Collaboration is also required regarding the definition and standardisation of V2X messages and protocols. The mechanisms proposed in TransAID to improve the reliability of V2X messages can be key in the near future. In general, V2X communications solutions require to be incorporated into standards to be effectively deployed. That is the case for, for example, collective perception solutions, message generation rules for manoeuvre coordination, V2X message compression or broadcast acknowledgement mechanisms. In TransAID we have been intensively working to promote and disseminate all the proposed solutions in top-tier journals and international conferences, as well as in organisations like ETSI and C2C-CC.

The above shows a broad range of aspects studied by TransAID in the very dynamic and rapidly evolving field of automated driving. To provide links to additional information and to place the work of TransAID into context, Chapter 5 provides an overview or close related initiatives.

1 Introduction

In the following sections, we first give a concise overview of the TransAID project, then highlight the purpose of this document, and finally present its structure.

1.1 About TransAID

As the introduction of automated vehicles becomes feasible, even in urban areas, it will be necessary to investigate their impacts on traffic safety and efficiency. This is particularly true during the early stages of market introduction, where automated vehicles of all SAE levels, connected vehicles (able to communicate via V2X) and conventional vehicles will share the same roads with varying penetration rates.

There will be areas and situations on the roads where high automation can be granted, and others where it is not allowed or not possible due to various reasons (missing sensor inputs, highly complex situations, etc). Consequently, there will be areas where many automated vehicles will need to change their level of automation to adopt more conservative operations or even give the control back to manual driving (Transition of Control, ToC in short). We refer to these areas as “Transition Areas” (TAs).

It can be expected that especially at Transition Areas the simultaneous presence of automated, connected, and conventional vehicles will be challenging and possibly negatively affect safety and traffic efficiency. To cope with these challenges, TransAID develops and demonstrates traffic management procedures and protocols to prevent or mitigate the negative effects of ToC at TAs, hence enabling smooth coexistence between different types of automated and non-automated vehicles. A hierarchical approach is followed where control actions are implemented at different layers including centralised traffic management, infrastructure, and vehicles.

First, simulations are performed to find optimal infrastructure-assisted management solutions to control connected, automated, and conventional vehicles at Transition Areas, taking into account traffic safety and efficiency metrics. Then, communication protocols for the cooperation between connected/automated vehicles and the road infrastructure are developed. Measures to detect and inform conventional vehicles are also addressed. The most promising solutions are then implemented as real world prototypes and demonstrated under real urban conditions. Finally, guidelines for enabling the TransAID vision on advanced infrastructure-assisted driving are formulated. These guidelines also include a roadmap defining activities and needed upgrades of road infrastructure in the upcoming fifteen years (i.e., the average life cycle of physical and digital infrastructure) to guarantee a smooth coexistence of conventional, connected, and automated vehicles.

Iterative project approach

TransAID performs its development and testing in two project iterations. Each project iteration lasts half of the total project duration. During the first project iteration, the focus is placed on studying Transitions-of-Control (ToCs) and Minimum-Risk Manoeuvres (MRMs) using simplified scenarios. To this end, models for automated driving and ToC/MRM are developed and adopted. The simplified scenarios are used for conducting several simulation experiments to analyse the impacts of ToCs at TAs, and the effects of 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 and realism of the tested scenarios is increased by also combining multiple simplified scenarios into new and more complex use cases.

1.2 Purpose of this document: the meta-analysis

This deliverable will aggregate, integrate, and analyse the results of the TransAID work packages. For each aspect of TransAID the major findings are presented and discussed. Specifically, for each of the selected use cases in D2.2 the effects of the TransAID measures are summarised and discussed, highlighting the effects of the measures to emissions, safety and efficiency.

Furthermore, knowledge gaps that were found during the TransAID project will be presented and lessons learned will be discussed. As a result, best practices for dealing with transitions of control, especially in transition areas, and other phenomena related to highly automated driving are documented.

All in all, the deliverable provides a summary of all the projects most important findings, gaps, recommendations and lessons learned. There is one exception and that is some the other work of WP8. That WP created a stakeholder consultation report (D8.1) and a guidelines and roadmap document (D8.3¹). D8.1 has indirectly provided input to the work of the other WPs, but the findings are not explicitly documented here. For that, see the summary in Section 5 of D8.1.

Finally, conclusions are made along the line of the sub-objectives of the TransAID project to assess to what extent TransAID has met its objectives.

1.3 Structure of this document

First, an overview of the major findings for each of the major aspects of the TransAID project is presented. Next, gaps and recommendations are described to indicate what was missing in the approach and which improvements are recommended for future work. Specific lessons learned regarding the topics covered by TransAID are discussed as well as a reflection on the process of the TransAID project (e.g. two iterations, simulation implementation). For reference, we then present a chapter providing links to several other initiatives related to topics covered by TransAID for those who want to learn more about those topics. That chapter also indirectly positions TransAID in the current research field for future reference. Finally, we reflect on the work done by TransAID from the perspective of the sub-objectives defined in the project proposal.

1.4 Glossary

ACC	Adaptive Cruise Control
ACK	Acknowledgement
AD	Automated Driving
ADAS	Advanced Driver Assistance Systems
AI	Artificial Intelligence
AV	Automated vehicle
C2C-CC	CAR 2 CAR Communication Consortium

¹ D8.3 is being written at the time this deliverable (D8.2) is finalised.

CACC	Cooperative adaptive cruise control
CAD	Connected and Automated Driving
C-ITS	Cooperative intelligent transportation systems
CAD	Connected and Automated Driving
CAM	Cooperative Awareness Message
CAV	Cooperative and Automated Vehicle
CCAM	Cooperative Connected and Automated Mobility
GDPR	General Data Protection Regulation
COVID-19	Coronavirus Disease 2019
CPM	Collective Perception Message
CPS	Collective Perception Service
CPU	Central Processing Unit
CV	Cooperative Vehicle
DCC	Decentralised Congestion Control
DENM	Decentralised Environmental Notification Message
Dx.y	Deliverable from work package x with sub-id y.
EC	European Commission
ETSI	European Telecommunication Standards Institute
EU	European Union
GLOSA	Green Light Optimal Speed Advisory
HARQ	Hybrid Automatic Repeat Request
HMI	Human Machine Interface
iCS	iTETRIS Control System
iTETRIS	integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions
I2V	Infrastructure to Vehicle Communication
ICT	Information and Communication Technologies

IEEE	Institute of Electrical and Electronics Engineers
EIP	European ITS Platform
ISAD	Infrastructure Support Levels for Automated Driving (see Section 1.4.2)
ITS	Intelligent Transportation Systems
IV	Intelligent Vehicle
KPI	Key Performance Indicator
LED	Light Emitting Diode
LIDAR	LIght Detection And Ranging of Laser Imaging Detection And Ranging
LOS	Level Of Service (from Highway Capacity Manual)
LTE	Long Term Evolution (cellular communication)
MAC	Media Access Control
MAPEM	Map Message
MCM	Manoeuvre Coordination Message
MCS	Manoeuvre Coordination Service
MRM	Minimum-Risk Manoeuvre
(N)RA	(National) Road Authority
ODD	Operational Design Domain (see Section 1.4.1)
OEM	Original Equipment Manufacturer
PT	Public Transport
RDS	Radio Data Service
RSI	Road Side Infrastructure
RSS	Responsibility-Sensitive Safety
RSU	Roadside Unit
SA	Sub-activity
SAE	Society of Automotive Engineers
SPATEM	Signal Phase and Time Message

SUMO	Simulation of Urban MObility
TA	Transition Area
TMC	Traffic Management Centre
ToC	Transition of Aontrol
TOR	Take Over Request
TraCI	Traffic Control Interface
TransAID	Transition Areas for Infrastructure-Assisted Driving
TR	Technical Report
TS	Technical Specification
US DoT	United States Department of Transport
V2X	Vehicle to Anything Communication
VMS	Variable Message Sign
VRU	Vulnerable Road User
WP	Work Package

1.4.1 ODD

The Operational Design Domain (ODD) is a description of the specific operating conditions in which the automated driving system is designed to properly operate, including but not limited to roadway types, speed range, environmental conditions (weather, daytime/night time, etc.), prevailing traffic law and regulations, and other domain constraints.

1.4.2 ISAD

The environmental perception of automated vehicles is limited by the range and capability of on-board sensors. Road infrastructure operators already employ numerous traffic and environmental sensors and provide information that can be perceived by automated vehicles. In order to classify and harmonize the capabilities of a road infrastructure to support and guide automated vehicles, INFRAMIX² has proposed a simple classification scheme (see Figure 1), similar to SAE levels for the automated vehicle capabilities (Manganariis, 2019; Amditis, 2019). These levels can be assigned to parts of the network in order to give automated vehicles and their operators guidance on the “readiness” of the road network for the coming highway automation era.

Infrastructure support levels are meant to describe road or highway sections rather than whole road networks. This reflects common practice of infrastructure deployment: Traffic control systems (sensors and VMS) are usually deployed on motorway sections where traffic often reaches the

² <https://www.inframix.eu/>

capacity limit (e.g. in metropolitan areas), whereas other motorway sections need no fixed installations of traffic control systems because traffic flow is rarely disrupted. If a complex intersection is covered by dedicated traffic sensors, traffic situation awareness (level B) and even AV guidance (level A) could be provided. Other sections provide only level C support, which includes that VMS data is made available via digital interfaces. Furthermore, in this example the secondary road network is covered partially by map support (Level D), some rural areas have no support. This example illustrates how ISAD levels can be used for a simple description of what automated vehicles can expect on specific parts of a road network.

	Level	Name	Description	Digital information provided to AVs			
				Digital map with static road signs	VMS, warnings, incidents, weather	Microscopic traffic situation	Guidance: speed, gap, lane advice
Conventional infrastructure	E	Conventional infrastructure / no AV support	Conventional infrastructure without digital information. AVs need to recognise road geometry and road signs.				
	D	Static digital information / Map support	Digital map data is available with static road signs. Map data could be complemented by physical reference points (landmarks signs). Traffic lights, short term road works and VMS need to be recognized by AVs.	X			
Digital infrastructure	C	Dynamic digital information	All dynamic and static infrastructure information is available in digital form and can be provided to AVs.	X	X		
	B	Cooperative perception	Infrastructure is capable of perceiving microscopic traffic situations and providing this data to AVs in real-time.	X	X	X	
	A	Cooperative driving	Based on the real-time information on vehicle movements, the infrastructure is able to guide AVs (groups of vehicles or single vehicles) in order to optimize the overall traffic flow.	X	X	X	X

Figure 1: Levels of the Infrastructure Support for Automated Driving

2 Summary of the results

This chapter presents the major findings, assumptions, and a discussion of the results of the TransAID project. These results come from the work done in WP2 to WP7. The other WPs are not represented in this document, since these work packages are related to project management, dissemination, and knowledge transfer and exploitation.

2.1 The assessment of vehicle automation

As a basis for studying mixed traffic in transition areas through simulations, the behaviour of the different vehicle types needs to be modelled. WP3 focussed on creating these realistic models and used them together with the use cases defined in WP2 to create a baseline. Below the major findings regarding those vehicle models are reported and discussed.

In TransAID we developed models to replicate functions of automated driving systems, and driver-vehicle interactions (in the context of automated driving) in the microscopic traffic simulator SUMO. Namely, the following vehicle and driver models that can dictate CAV longitudinal motion, lateral motion, and driving behaviour during ToC/MRM:

- an ACC/CACC model adopted from a previous study and modified to ensure collision-free car-following behaviour
- a parametrised version of SUMO's default lane change model (by means of a sensitivity analysis) to reflect the actual (OEM-specific) CAV lane change behaviour
- a decentralised cooperative lane change algorithm
- a ToC/MRM algorithm (based on literature findings)

The development of the latter models in SUMO enabled the impact assessment of mixed traffic conditions in terms of traffic efficiency, traffic dynamics, traffic safety, and environmental impacts. We setup and run simulations experiments that did not encompass traffic management measures (baseline) considering three distinct dimensions (the traffic demand level, the traffic mix, and the driver model parametrisation scheme) to capture the effects of ToCs/MRM for different traffic conditions, traffic compositions, and vehicle properties. ToC/MRM impacts were investigated at work zones (use cases 1.1 and 4.2), motorway merge and diverge segments (use cases 2.1, 1.3, and 3.1), incident locations (use case 2.3), and no-AD zones (use cases 4.1 – 5.1). Day 1 C-ITS applications were also addressed in the context of use cases 2.1, 2.3 and 4.2, to enhance the realism of our simulation experiments for future baseline scenarios.

From the baseline simulation runs we found that ToCs do not significantly disrupt traffic flow performance unless CAVs establish increased car-following headways during the ToC preparation phase (automation system controls vehicle motion during the available lead time). Disruptions escalate in case of CACC driving, increased share of CAVs in the fleet mix, and the occurrence of multiple ToCs within a narrow temporal window and spatial domain. Furthermore, in the case that a ToC is unsuccessful or not possible, unmanaged MRMs (taking place in lane and not being guided towards safe spots) can induce significant traffic disruption as well. The magnitude of the disruption is affected by the driver response time (amount of time required to resume vehicle control after MRM) and the prevailing traffic intensity. Traffic breakdown probability diminishes when drivers of CAVs take over vehicle control shortly after (time window encompassing few seconds) the execution of MRM. On the other hand, simulation results indicated that cooperative lane changes minimize the frequency of ToC/MRM and their consequent adverse impacts on traffic flow operations. The benefits of cooperative lane changing are amplified with increasing share of CAVs and especially upstream of lane drop locations.

Increased shares of CAVs in the fleet mix have two negative effects in mixed traffic conditions. Firstly, throughput is reduced when lane change behaviour of CAVs is more conservative compared to manual driving. Secondly, conflict risk increases in the proximity of lane drop locations (e.g., work zones and merge segments) for the same reason and in situations where the frequency of ToCs/MRMs is high. However, it should be also noted that the ACC/CACC model uses speed differences in a linear way although speed impacts braking gaps and thus safety requirements in a quadratic way. Hence, the safety critical events that are reported due to car-following reasons (which are the majority among safety critical events) can also occur due to systematic issues concerning the ACC/CACC model formulation.

2.1.1 Discussion

The behaviour of automated vehicles during the assessment was based on three assumptions. Firstly, lane changing behaviour of CAVs in the microscopic traffic simulator SUMO was modelled to replicate the actual lane change logic of a prototype AV, which is more conservative compared to lane changing of manually driven vehicles. However, highly automated driving might enable human-like (less conservative) lane changing activity from the CAV side. Secondly, ACC/CACC models were used to emulate the car-following logic of CAVs. Nonetheless, TransAID considers CAVs of higher automation level in the context of its simulation experiments as well. In the absence of publicly available information with respect to car-following capabilities of highly automated vehicles the latter ACC/CACC models dictate the car-following logic of CAVs in SUMO irrespective of the CAV's automation level. Thirdly, the ToC model was developed based on a solid theoretical background. However, vehicle trajectory data pertaining to vehicle disengagements are required for the calibration of the ToC model behaviour during the recovery phase (data from the sim^{TD} database were used to model erratic driver behaviour during the post ToC phase).

2.2 Enhanced traffic management measures

Building upon the use cases defined in WP2 and the vehicle models and simulations set up in WP3, WP4 developed specific traffic measures to mitigate the effects of ToC events in transition areas. The traffic measures were implemented to study their effectiveness. In this stage, communications were not yet added to assess the full potential of the measures. In WP6, based on the work done on communications in WP5, the use case studies are repeated with communications (enabled) to assess the impact of that additional factor.

In addition, we studied the different roles associated with the identification and management of transition areas. A proposal for the roles and associated responsibilities were captured via the design of a traffic management framework in the form of an intermediary service.

2.2.1 Traffic management framework

As a start to find effective traffic measures, an overview of the state of the art in traffic management was created. First, we looked to general approaches where the underlying principle is not to just look at single locations, but rather to use the entire network to distribute traffic more wisely and as such postpone or even prevent the formation of congestion. Some promising techniques in this respect are coordinated network-wide traffic management (including regional traffic management), using key performance indicators to make the entire process performance-based and more cost effective, hierarchical controls that are implemented via layered architectures (spanning the range from top-down regulation over self-organisation to full bottom-up regulation), and Traffic Management as a Service.

Next, we looked at the trend towards more cooperative systems which are well-suited for enhanced traffic management. This makes the systems smarter, in that – as opposed to the classic approach whereby large groups of road users are targeted – we can now target vehicles individually given a sufficient level of penetration of cooperative vehicles. Going even further, the collaborative approach for automated vehicles is also a direction in which future traffic management systems are evolving.

Finally, we looked at the expected impacts that machine learning techniques and artificial intelligence in general can have on traffic management. These are currently typically encountered in traffic light control and congestion / queue length predictions.

Another important result from the project was the outlining of a traffic management framework. We linked traffic management to the concepts of goals, policies, and strategies. Examples of such goals are minimising congestion, improving the network capacity, and improving the network resilience against disturbances. Examples of policies are pay according to generated pollution, adopting city access restrictions, and encouraging electric vehicles. And, finally, examples of strategies are low-emission zones, road usage charging, subsidies for purchasing electric vehicles, and installing chargers for electric vehicles. We also considered traffic management from an EC perspective with special emphasis on the C-ITS platform, ITS Action Plans (with priority actions and areas), and Sustainable Urban Mobility Plans.

Within this context, we scoped the outline of a suitable traffic management framework. Here we positioned TransAID as an intermediary service provider, acting as a trusted (and possibly mandated) third party. The framework allows TransAID to be scaled up and generalised. We approached this from both a technical and a business-oriented perspective. For TransAID to become part of a complete traffic management system, we focused on the technical side on how to detect transition areas, select (and possibly combine) services, and then detect when they are most appropriately timed for deployment. To this end, detection can be done via the infrastructure (e.g. road sensors or even digital communication infrastructure), via the OEMs, or by comparing an infrastructure's newly-defined

ISAD level (Infrastructure Support levels for Automated Driving; see Section 1.4.2) to the operational design domain (ODD, see Section 1.4.1) of the vehicle. From a business-oriented perspective, TransAID requires collaboration with both OEMs and (national) road authority ((N)RAs).

Considering the mentioned technical challenges (detecting TAs, selecting services, and timing their deployment), the intermediary service bridges all these parties in such a way that the detection of TAs is performed in a centralised way, and OEMs and (national) road authorities ((N)RAs) have a single point of contact for providing and receiving information about TAs.

The information and data flow in this construction is multidirectional, as for example the intermediary service can also provide support to the OEMs by sharing the locations of identified TAs and changes to ISAD. This can then in turn help the OEMs to improve their systems, because they now have specific examples of situations where the limits of their ODDs are reached.

And finally, considering the detection of TAs we foresee two different time scales at which TransAID's traffic management service will operate, i.e. a slower changing situation corresponding to a more strategic level that leads to static transition areas, such as changes to infrastructure or roadside systems, and a faster changing situation leading to dynamic transition areas (because of changing weather conditions such as fog and heavy snow, incidents, or other specific traffic conditions), requiring timely action.

2.2.2 Assessment of traffic measures in Transition Areas

In addition to outlining a traffic management framework, WP4 evaluated the different selected services and use cases of which an overview is given in Figure 2. These were selected via an expert rating process from the set of created services and use cases in WP2. Also, in WP2 traffic measures to mitigate the effects of ToCs in TAs were already defined on a high level. WP4 refined those measures and created the necessary detailed logic to implement them in the simulations created in WP3. The details of that logic and implementations are described in the deliverables of WP4. Below we summarise the results for each of the selected use cases. All selected services and use cases were assessed and measured by KPIs for traffic efficiency (network-wide average speeds and throughput, and local tempo-spatial diagrams), traffic safety (the number of events with a time-to-collision smaller than 3 seconds), and the environmental impact (the estimated CO₂ emissions).

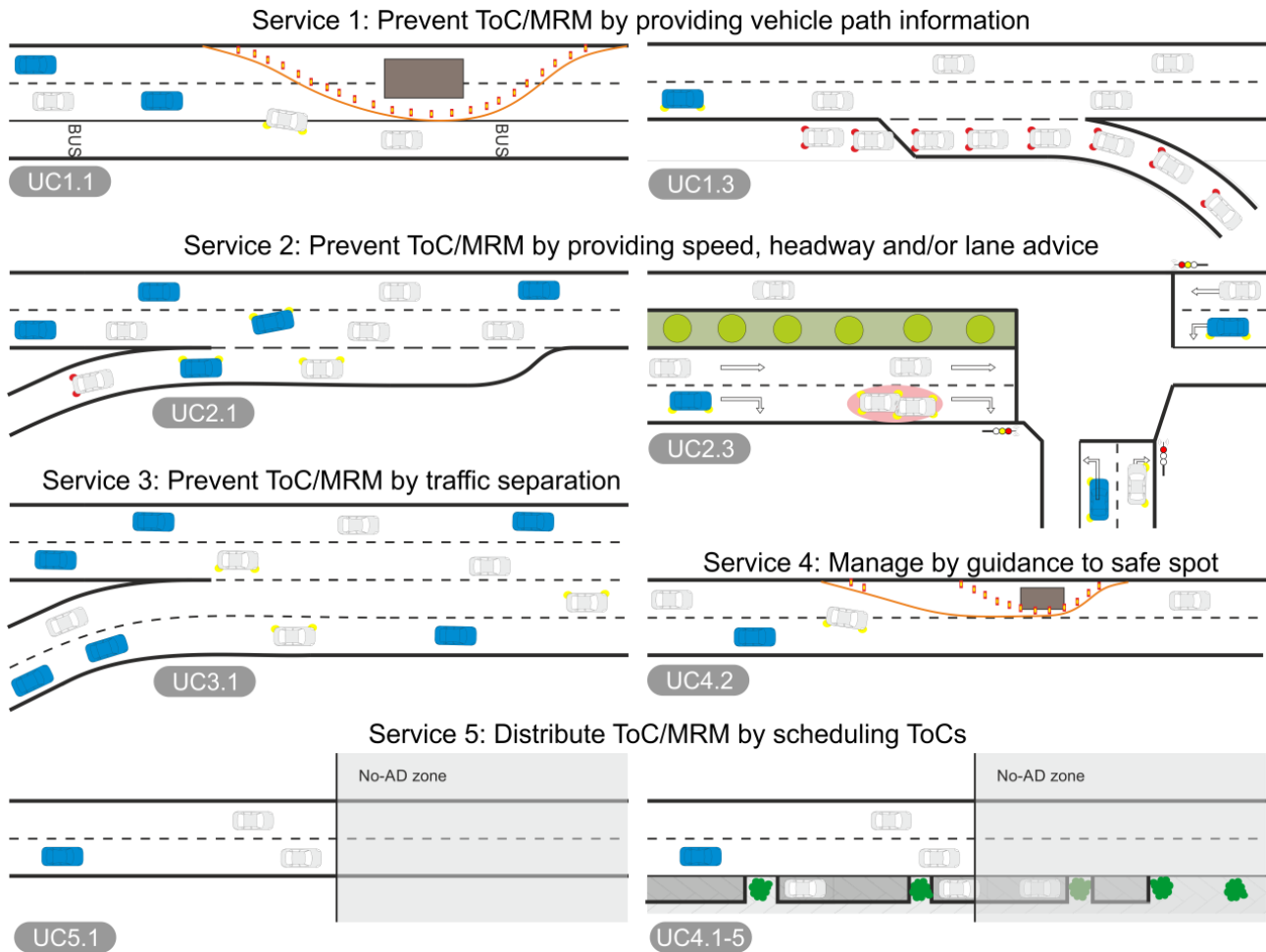


Figure 2: Schematic overview of the TransAID services

Specific results for the individual use cases are:

Use case 1.1: Path information was provided to CAVs to circumvent road works via a bus lane. Simulation results indicated that overall traffic efficiency and CO₂ emissions remained unchanged, while traffic safety was improved significantly. Safety critical events were reduced ranging from 45% to 70%, depending on the level of service and traffic composition. The reduction was larger in case of less traffic and more AVs.

Use case 1.3: Queue spillback at exit ramp. The simulations with traffic management show a significant reduction of the queuing, especially on the main road. This has a beneficial effect on all indicators. The average travel time decreases, despite the speed limits applied in the traffic management scenario. The impact on the average travel time due to the extra capacity generated by opening the emergency lane for queuing exceeds the increase caused by the speed limits. The number of lane changes reduces as the LOS increases, the vehicle mix does not impact the number of lane changes significantly. The number of lane changes only slightly decreases from the baseline to the traffic management scenario. The throughput increases strongly between LOS B and LOS C in the traffic management scenario. There is no significant impact of the vehicle mix on the throughput. Compared to the baseline, the scenario with traffic management has a slightly higher throughput, especially for LOS C and LOS D. The average number of safety-critical events increases with the LOS and with the share of CAVs in the vehicle mix, but it is still significantly reduced compared to the baseline. As the LOS increases, queue length grows, and therefore speed differences and the occurrence of critical events both increase. CAVs that cannot find an appropriate gap in the queue to

merge can stop on the main route for up to 10 seconds until they finally merge or finally reroute. These vehicles cause perturbations on the lanes of the main road, which can cause an increase in TTCs. CO₂ emissions increase slightly with the LOS and with the share of CAVs in the vehicle mix. The queue length increases as the share of CAVs increases in the vehicle mix. The CO₂ emissions correlate with the queue length, due to stop-and-go traffic in the queues.

Use case 2.1: A motorway merge area where CAVs are given speed advice to merge onto the motorway and preventing a ToC/MRM by providing speed, headway, and/or lane advice. The inclusion of ramp metering (using the merging assistant system algorithm) reduced the ToC percentage by means of gap searching, speed advice, and gap creating via pairing. In addition, the number of lane changes also decreased under the control logic as well as the variations between runs, showing improvement on homogeneity of traffic flow. There was a slightly negative effect on traffic efficiency and environmental impact, which could be correlated to the conservative parameter settings of the merging assistant system and ramp metering configuration. The control logic strengthened safety objectives. Less late merging and no end-of-the-acceleration-lane merging will happen, which would impact the performance of average travel time and average network speed, especially under heavier traffic demand due to lower capacity of the on-ramp. Thus, the merging assistant system and the intelligent ramp metering using this system shows the functional ability to prevent ToC and MRM. The trade-off between efficiency and ToC percentage is as expected for non-congested traffic situations. For congested traffic situations, ramp metering targeting lower ToC rates is not effective anymore because of expected increasing ToCs and MRMs of merging vehicles.

Use case 2.3: Intersection handling due to incident. CAVs and CVs receive information about the incident itself (position, type, etc.), and will also receive a reduced speed advice and are able to use another lane to turn right. Due to a timing plan update where the traffic coming from the incident road gets extra green time, the saturation and travel times in the traffic management scenario are up until LOS D. In the LOS D simulations, the building up of the queue is more persistent and propagates downstream in time. The impact of the incident is nevertheless less severe in comparison to the baseline.

Use case 3.1: A merging situation where two two-lane motorways merge into one four-lane motorway. The idea is to harmonise traffic by assigning the outer lanes to CAVs, thereby reducing close interactions between non-automated vehicles and CAVs in the merging area. Only in case of higher shares of CAVs (> 25% level 2, > 25% level 3) in combination with LOS B or C, improvements were observed in throughput at the cost of slightly lower average network speeds and a decrease in safety. In short, rearranging traffic to dedicated lanes shows largely similar performance to ‘uncontrolled merging’ (i.e., no measures). However, we hypothesise that separating traffic can outperform uncontrolled merging when cooperative manoeuvring is applied.

Use case 4.2 (1st iteration): A two-lane road with safe spots upstream of a road works zone on the left lane for CAVs to stop in case they reach the limit of their ODD. In this case the open right lane remains unblocked. As expected, traffic, safety and environmental benefits are realised. Only in case of congestion, when traffic is already moving slowly, the improvement diminishes.

Use case 5.1 (standalone): A no-automated driving zone was simulated along the downstream part of a two-lane motorway. The zone can represent different situations (e.g., road works, geofences, weather, accidents, ...) that prevent CAVs from staying in automated driving mode. It is assumed that AVs increase their headway before handing over control to the driver. When this happens in a concentrated fashion just before the no-AD zone, traffic flow is impacted. We therefore distribute these handovers in time and space upstream of the zone. It was found that this service greatly smoothens out the disturbances caused by the handovers and improves traffic efficiency.

Use case 4.1+5.1 (combined): Distributed safe spots along an urban corridor. The introduction of the proposed traffic management logic achieves overall improvements regarding all KPIs. With respect

to the nature of the overall behaviour of this use case with spontaneous parking activities and severe MRM manoeuvres, the enhancements, brought by Service 4, have great impact on the traffic system, which ultimately shows in the traffic safety KPI. Due to the adjustment of ToC lead times, more MRM manoeuvres appear in the traffic management case. Moreover, the main objective of the current safe spot assignment logic is to provide the best suitable safe spot target given a CAV's position, the current traffic state, and parking space availability. A free safe spot cannot be guaranteed in any case. Therefore, some MRMs still occur on the road not only due to the capacity limitation of the safe spots, but also due to spontaneous real-life parking behaviour. In conclusion, Service 4 in combination with Service 5 greatly improves the performances of all KPIs with the significant contribution of the safe spot assignment especially in regard of traffic safety, whereas Service 5 expectedly has proportionally greater impact on traffic efficiency and emissions as already indicated in the first iteration for simulations of use case 5.

Use case 4.2 (2nd iteration): Safe spot in lane of blockage & lane change assistant. The simulation results for both the urban and motorway networks indicate that infrastructure-assisted traffic management and cooperative driving can generate traffic efficiency, traffic safety, and environmental benefits in the vicinity of Transitions Areas. CAV guidance to safe spots, lane advice (change/keep) provision from the RSI, and distributed cooperative manoeuvring reduce traffic disruption induced by MRMs in lane, dynamic TORs, and non-homogeneous lane change behaviour in the proximity of lane drop bottlenecks (e.g., work zones). Specifically, reported results show that average travel time, shockwaves, lane change intensity, TORs, safety critical events, and CO₂ emissions reduce for Traffic Management scenarios, while throughput increases.

Common results for all the use case are:

There is a trade-off between traffic safety versus traffic efficiency (as measured via throughput and travel times). It is often inherently difficult or even impossible to optimise both in the same context. Hence, typically a policy choice needs to be made, as to which of the two will have to be prioritised.

There is also a heavy dependence of the results on the mixture of vehicle types, in addition to the observation that less efficient traffic management performance is obtained for a higher LOS. The latter is in part logical, as for higher LOS there is more prominent congestion and the physical limits of the infrastructure remain a hard obstacle. By itself this is not a problem for TransAID, as the focus of the traffic management schemes is to prevent/postpone traffic breakdowns before they occur.

Regarding merging operations, our results indicate that separating traffic can outperform uncontrolled merging in case cooperative manoeuvring is applied. Furthermore, distributing the handovers in time and space upstream of a no-AD zone smoothens out the disturbances caused by them and improves traffic efficiency. More strongly, traffic safety increases when safe spot are explicitly assigned by the traffic management system to the requiring vehicles.

2.2.3 Discussion

All TransAID services and use cases present solutions that take the form of one or more of three (combined) actions, i.e. (i) prevent ToC/MRM, (ii) manage or support ToC/MRM, and (iii) distribute (in time and space) ToC/MRM.

All previously stated obtained results assume that communications between vehicles among themselves and between them and the infrastructure happen instantaneously and without any bandwidth limitations. Information was also ubiquitously available to all vehicles and infrastructure elements.

The results are each time based on a large number of simulations, whereby a range of possible combinations was assessed, consisting of three vehicle mixes times three to four levels of service.

Each result was the average of ten individually differently random-seeded simulation runs, similar to the baseline as simulated in WP3.

Regarding the validity of the simulation results we note that they provided general trends and ideal expectations of the proposed traffic management services. However, due to the lack of realistic communications, the results are sometimes more optimistic than they would be otherwise as shown in Section 0 where the results of WP6 (use cases with communications enabled) are discussed.

Other aspects that are interesting to consider but currently out of scope are (i) simulations of the other use cases, (ii) of other vehicle mixes, (iii) adopting a finer LOS discrimination, and (iv) simulating more complex road stretches and subsequently chained use cases.

2.3 Communication at Transition Areas

TransAID started with the definition of scenarios and use cases in WP2 and created the required vehicle models, simulations, and traffic measures in WP3 and WP4. To bring the simulations to a next level or realism, communications need to be added. WP5 focussed on identifying or creating the right message sets and protocols to make that possible. Based on this work the use cases could be simulated with communications in WP6. Below, the major findings regarding TransAID's work on communications are discussed.

2.3.1 V2X communications

The introduction of CAVs on the roads requires the redefinition of the standard V2X messages available to allow the development of the full capabilities of CAVs and support of the TransAID services. Any extension proposed on top of these standards should ensure backwards compatibility with original solutions as well as interoperability with already existing systems. From the TransAID project, we have contributed to the definition of new messages and the extension of existing ones to increase the capabilities of CAVs:

- ETSI CAM needs to be extended to provide data to allow CACC strings and data to facilitate the assistance of the infrastructure in cooperative manoeuvres (e.g., current/maximum automation level).
- ETSI DENM needs to be extended to alert other actors (i.e., other road users, RSI) when ToCs or MRMs occur in CAVs and to announce areas where driving in autonomous mode is restricted.
- ETSI MCM needs to be defined to allow vehicles to exchange information about their intended trajectories, to enable the manoeuvre coordination between CAVs and to support the assistance of the infrastructure to improve the cooperation of vehicles.
- ETSI MAPEM should be updated to include special permissions or restrictions to drive in automated mode (e.g., emergency lanes, bus lanes) and to describe new types of areas such as safe spots for CAVs performing MRMs.

In TransAID, we have not identified the need to create new messages. In most cases the information needed to support TransAID use cases and services is already available in the current standardised messages and only minor extensions are needed.

Manoeuvre coordination will be key to support the TransAID traffic management measures. There are multiple types of scenarios where manoeuvre coordination is needed. Therefore, it is necessary to define a Manoeuvre Coordination Service that is valid for all types of scenarios.

Aligned with the work of ETSI, TransAID has proposed a Manoeuvre Coordination Service where the infrastructure takes an active role to facilitate the manoeuvres of vehicles and to increase the overall traffic flow and safety. Note that vehicles will look for the increase of their own safety and efficiency given their own information. However, the local decisions taken by CAVs may not coincide with the overall decisions considering all the traffic flow that can be computed by the infrastructure due to its increased environmental awareness (higher V2X communications range, additional sensors available, etc.).

With this approach, TransAID has actively contributed to the ETSI standardisation process to introduce the participation of the road infrastructure in the manoeuvre coordination process. To enable the coordination of CAVs (with and without the support of the road infrastructure), efficient and reliable message generation rules that enable the exchange of MCMs are needed. This is particularly the case given the early stages of the ETSI standardisation work on this topic. MCM generation rules must be dynamic and adapt to the variations of the trajectories transmitted and the environmental risk with other vehicles to fulfil the two main objectives of the exchange of MCMs,

which are: a) enable the manoeuvre coordination and b) inform other vehicles about current ego-vehicles intentions.

Two main message generation rules have been designed in TransAID that can cope with the requirements of the MCM while maintaining at low levels the congestion of the communications channel. On the one hand, the *risk* approach measures the risk of vehicles with their neighbour and adapts the transmission rate so more MCMs are transmitted more frequently when there exists a risk with another vehicle and MCMs are transmitted less frequently in the absence of risk. On the other hand, the *tracking trajectories* approach measures the variations between the trajectories transmitted by a vehicle and only transmits a new MCM when there exists a significant variation. Its goal is to avoid unnecessary redundancy and increase the amount of new information transmitted in each MCM. These two approaches have been extensively evaluated in TransAID by means of simulations.

The traffic management measures designed in TransAID also require that CAVs and road infrastructure units have an accurate perception of the environment. TransAID has contributed to the evaluation and evolution of ETSI's Collective Perception Service (CPS) for cooperative perception. We have demonstrated that cooperative perception can improve CAVs perception capabilities when the trade-off between the perception capabilities and communications performance is balanced. To this aim, different functionalities of cooperative perception have been analysed in detail in TransAID and evolved. The major findings are listed below:

- TransAID has identified and evaluated the sensor devices and techniques needed to fuse their data for an accurate local perception of the environment. This includes techniques implemented at camera-equipped infrastructures that can detect, create bounding boxes, and uniquely track objects using optical flow, and at the vehicle employing a hybrid sensor fusion strategy which contains a low-level LIDAR fusion module, that transforms the sensor data of multiple laser scanners into a common coordinate system, and an object-level fusion module, that fuses in-vehicle sensor data with data coming from neighbouring vehicles.
- A key aspect for the efficient execution of the CPS is the definition of appropriate generation rules for the transmission of the CPMs (Collective Perception Messages), i.e., how often they are transmitted and what information do they include. TransAID has conducted a comprehensive analysis of the effect on the communications performance and information awareness of the CPM generation rules that are being considered in ETSI. The conducted analysis has shown that there is a trade-off between perception capabilities and communications performance/scalability: vehicles detecting the same object(s) and including them in their CPMs create redundant detection which can help improve the perception capabilities but generate higher channel load levels and therefore impact the performance of V2X networks. This analysis has therefore revealed certain weaknesses of the ETSI CPM generation rules that need to be solved.
- Based on the above-mentioned analysis of the ETSI CPM generation rules, TransAID has proposed and evaluated advanced policies to further optimize the CPM, both its content and transmission triggering conditions. The goal is to achieve the necessary levels of redundancy and minimize the impact of the implementation of CPM in the stability and scalability of future V2X networks:
 - a) The *look-ahead* mechanism is designed to reduce the number of CPM transmitted with a small number of objects by the prediction of objects that will need to be transmitted in a near future. The transmission of small CPMs decreases the communications efficiency by increasing the proportion of overhead (e.g., packet headers) transmitted compared to the amount of information (i.e., detected objects). With *look-ahead*, the channel load is reduced and the perception capabilities of CAVs are increased. This mechanism has been designed and proposed by TransAID and is part of the ETSI Technical Report of collective perception (TR 103 562).

- b) When an object is detected by multiple CAVs and/or infrastructure units, it is reported multiple times. This increases the amount of redundant information received, which in many cases can be unnecessary. TransAID identified the need of defining a redundancy mitigation mechanism that limits the transmission of objects that have been recently transmitted by a neighbouring vehicle. We proposed and evaluated a mechanism to reduce redundancy that can reduce the channel load between 20% and 60% approximately, depending on the configuration, while maintaining high perception levels of for safety-critical short and medium distances. This mechanism is also part of the ETSI Technical Report of collective perception.
- c) In TransAID we have also proposed two methods to combine the redundancy mitigation technique and the look-ahead mechanism previously described. This combination improves the overall effectiveness of cooperative sensing, reducing the channel load and improving the perception capabilities of CAVs.

Another major finding of TransAID is related to the reliability of V2X message exchange. Most V2X applications rely on the exchange of broadcast messages that lack mechanisms to ensure the correct delivery of each message. The reliability of V2X communications has been addressed in TransAID using different and complementary techniques: compression, congestion control and acknowledgements.

- TransAID has proposed and evaluated for the first time the use of V2X message compression. We have demonstrated that the compression of real-world CAM, CPM, and MCM messages (obtained from real-world experiments) can produce a significant message size reduction. The benefits of reducing the messages' size thanks to V2X message compression has an impact on the V2X channel load and interferences, which finally result in an improvement of the reliability of the V2X communications. This benefit is achieved without reducing the amount of information and frequency of the V2X messages.
- ETSI's Decentralised Congestion Control (DCC) at the Access layer is used to control the rate at which V2X messages are transmitted to the radio channel. When the number of messages generated by the upper layers is higher than the number of messages that can be transmitted, DCC can cause queue overflow and discard packets before they are transmitted. We have demonstrated that this has an impact on the V2X applications reliability, with both the Adaptive and Reactive approaches for DCC Access.
- To partially address the limitations of DCC Access, we have evaluated for the first time the combination of DCC Facilities and DCC Access for the transmission of V2X messages. DCC Facilities allows the adaptation of V2X message generation at the upper layers and internally distribute the resources available among the different applications and services running on the vehicle. TransAID has demonstrated the importance of DCC Facilities for the development of CAVs. This is particularly relevant considering that DCC Facilities is currently considered as optional and has not been adopted yet by industrial organisations like the C2C-CC.
- TransAID has proposed a method to improve the reliability of critical V2X messages. We have proposed the use of selective acknowledgements to improve the reliability of selected messages through their retransmission when target receiver(s) do not successfully receive them. Acknowledgements triggered by broadcast V2X messages can have scalability issues, and therefore only critical V2X messages should be acknowledged. The proposed mechanisms can be used to request acknowledgments only to a few receivers of broadcast V2X messages in order to avoid the collision of their ACK messages. Using the proposed mechanism, we have demonstrated that the reliability of V2X communications can be improved if the transmitter of the broadcast V2X message knows whether the intended receiver has correctly received the message or not, and whether a retransmission is needed.

A smooth introduction of automated vehicles in mixed traffic environments requires a mutual understanding between, and cooperation of, the different entities – being automated, connected or simply legacy vehicles. We have identified in TransAID the communication requirements to legacy vehicles, esp. by giving information about reasons of appearing situations, consequences and measures for avoiding negative impacts. Several existing technologies are introduced and their effectiveness in terms of the communication requirements is analysed. On this basis, the TransAID approach is a mixture of Variable Message Signs (VMS), static signage and an external HMI of CAVs is in focus. To also bridge to a more individual advice, also a web-service approach using mobile devices in the vehicles has been proposed and evaluated.

2.3.1.1 Discussion

It is important to point out the generic philosophy adopted for the definition of the TransAID V2X message sets. Rather than designing messages from the scratch, TransAID tries to reuse as much as possible the definitions of already available standard message sets. Any extension proposed on top of these standards is such to ensure backward compatibility with original solutions as well as interoperability with already existing systems. These are fundamental aspects to be considered to foster the future transfer of the TransAID results into current and upcoming C-ITS standardisation activities and hence real-world deployments.

The ETSI work on manoeuvre coordination is still at its early stages and TransAID has taken a lead role on this topic, assuming the challenge of defining and performing one of the first studies on this topic with realistic V2X communications. In the absence of public information about the algorithms employed by CAVs to generate their trajectories for manoeuvre coordination, a specific format and duration of the trajectories has been defined. Thus, the MCM message format defined may need some changes to adapt to different representations of trajectories. Moreover, changes on the format and duration will have an impact on the message size and therefore on the level of congestion of the communications channel.

Similarly, little information is available about what can be considered a risk situation between two vehicles, a general measure has been defined based on the time to a possible collision between the vehicles. However, this metric may be redefined in the future to include other types of dangerous situations.

ETSI has not yet defined the channel employed for the transmission of the MCM. In TransAID, we assumed that the MCM will share the channel with the CPM and CAM. If this is not the case, the channel load level obtained would be lower and the overall communications performance would be increased. However, other problems related to the use of multiple channels would emerge, such as the co-channel interference and the limitations of vehicles with only one radio interface, which can only transmit and receive using one channel.

The TransAID work on cooperative perception is having a high impact on the research community thanks to its adoption in the ETSI Technical Report about this topic. The conducted study, that evaluates the ETSI CPM generation rules and the proposed mechanisms considering two different highway traffic conditions and two different sensor configurations is one of the more detailed ones conducted to date. The obtained simulation results could be complemented with additional evaluation of urban traffic conditions and different sensor models from automated vehicle OEMs. ETSI is now working on the Technical Specification on this topic and will decide if the TransAID mechanisms (look-ahead and redundancy mitigation) will be mandatory or optional.

TransAID has proposed and evaluated for the first time the use of data compression techniques for V2X messages to improve the reliability of V2X messages. Compression techniques proposed in TransAID have been tested in general purpose PCs, and their performances in processors embedded in V2X modules might be different. In addition, a sample of V2X messages (CAMs, CPM, MCMs)

obtained from the trials conducted in TransAID has been used to test the compression gain of the compression techniques. This sample set has varying formats of each message (containers, etc.) and different sizes. The compression gain significantly depends on the content of the V2X messages and their size. Thus, the study could be complemented with additional results obtained from other set of V2X messages with different content and sizes.

In TransAID, the impact of congestion control functions at the Access and Facilities layers to improve the effectiveness of cooperative perception have been evaluated. We demonstrate that the combination of DCC Access and DCC Facilities increases the perception and reduces the information age when compared with the DCC Access configuration. We therefore demonstrate how critical the configuration of DCC Access is and the importance of DCC Facilities for the development of CAVs. The outcome of this study can provide them valuable knowledge towards an efficient and effective V2X configuration and deployment. The simulation environment considers the transmission of CAMs and CPMs in a single channel to evaluate the congestion control functions. This evaluation could be extended with other V2X messages like MCMs and DENMs, and they could also include more channels, in line with the current ETSI work on STF 585 about multi-channel operation.

The mechanisms proposed in TransAID to ensure the correct delivery of V2X messages are based on a cross-layer approach that first acts at the application layer by identifying the V2X messages that need to be acknowledged. At the application layer, the transmitting vehicle also identifies the receiving vehicle(s) that needs(need) to report with an acknowledgment whether the transmission was correctly received or not. The transmitter might be aware of the presence of the receiving vehicle by many means like for instance the reception of other V2X messages, or because it is detected with other sensors. In addition, once the receiving vehicle(s) has(have) been detected, a separate unicast packet is transmitted to request the transmission of such acknowledgments. Retransmissions of the broadcast V2X messages might be generated if the receiver(s) does(do) not acknowledge the reception of the message. Although the TransAID proposal has been designed considering the scalability issues that might arise in vehicular networks, there might be scenarios where multiple transmitters implement this mechanism in the same area. This might result in an additional load of the radio channel, and its impact on the reliability of the V2X communications needs to be evaluated.

The mechanisms proposed in TransAID to improve the reliability of V2X messages can be key in the near future. The motivation for improving the reliability of V2X broadcast messages is not only because of the added value for the V2X applications and services. Recent news has shown that the band where V2X communications operate might be shared with WiFi technologies (Proposed rule: 85 FR 6841). This might result in an increase of interferences in the 5.9 GHz band and potentially will compromise the reliability of V2X communications.

2.3.2 Communication to non-V2X road users

Besides the V2X communication, the communication to unequipped vehicles was in focus. Linked to TransAID, this part has two important sub tasks. On the one hand, infrastructure needs to inform unequipped vehicles about issues on the road. Second, automated vehicles themselves should provide information about their actual state to their surroundings, to avoid negative impacts.

With regards to the infrastructure information, it needs to be mentioned that visual information on signs, variable or static, will never be as precise as V2X communication could be, esp. when looking to individual advices. Nevertheless, infrastructure can provide valuable information also to unequipped vehicles by signage, e.g., in terms of speed limits, distance (gap) advice or dynamic lane assignments.

As unequipped vehicles in TransAID's terminology are also automated vehicles without communication, it is important to mention that those vehicles could interpret the signage of the

infrastructure in a more precise way. In this light, new signs may be useful, which will lead to early TORs and related ToCs, which has the potential to reduce negative impacts. It needs to be noted that these aspects have not been investigated in TransAID deeply, as we believe that future automated driving will automatically include any kind of electric communication, allowing for more precise and individual information.

Nevertheless, infrastructure will need to have a very good overview on the traffic situation to provide the best possible advice to all vehicles. This also includes specific reactions to different types of issues, including possible issues related to ToCs and MRMs inside and outside of TAs, as different reasons will require different measures, when the goal is finding the traffic management optimum.

In relation to information provided by individual CAVs to the surrounding traffic, research is currently at its start. As described in D5.4, but also highlighted by other projects like H2020 interACT³, it will be beneficial if automated vehicles give insights into their behaviour and plans. This is mandatory when thinking about interactions with pedestrians and bicyclists, but also at non-signalised intersections to give right-of-way. In our view, this also includes proper warnings if ToCs occur, and esp. when MRMs take place. Currently, CAVs will simply use their emergency flashers when indicating that they are about to stop, but that information channel is very limited. How can CAVs indicate that they are about to change lane to stop outside the driving lane when the emergency flasher is already in use? How would other road users react in TAs, when emergency flashers become very frequent, and no information is provided how the vehicles exactly will act? Therefore, TransAID identified that external light strips able to provide detailed information about the automation state and its goals, combined with the standard vehicle signage (e.g., indicators) should be introduced together with automated driving (see Figure 3).

Of course, this information could also be provided using electronic communication, but the needed related technology to receive such information needs to be present everywhere. Nevertheless, the optimal signage for automated vehicles to inform surrounding unequipped vehicles and others still needs to be found, requiring a lot of research. This also needs to consider other technological developments we will see and the reception of automated driving in the society until automated vehicles are getting omnipresent.

³ <https://www.interact-roadautomation.eu/>



Figure 3: simulated external light strips to provide detailed information about the automation state and its goals

2.4 Assessment of the traffic management procedures

Integrating the work done in WP3, WP4 and WP5, WP6 was able to study the selected services and use cases including communications, by simulating them using the iTETRIS (Rondinone et al., 2013) framework. Below we highlight some major findings regarding:

- The implementation of driver- and AV-models designed in WP3, traffic management procedures developed in WP4, and V2X communication protocols and models from WP5 within the iTETRIS simulation framework.
- Utilisation of this framework and implementation to investigate the impact of V2X communication on the proposed traffic management procedures.

Driver- and AV-models designed in WP3 haven been implemented in the microscopic traffic simulator SUMO, while traffic management procedures from WP4 have been implemented as an iTETRIS Application (or “TransAID App”). V2X communication protocols from WP5 have been integrated in the iTETRIS base code to facilitate V2X message exchange between vehicles and infrastructure as well as the simulation of wireless signal propagation, the latter of which has been taken out with either ideal propagation using the LightComm simulator or with realistic propagation using the ns-3 simulator. The complete simulation framework of the iTETRIS platform is shown in Figure 4. A detailed explanation about the different framework modules can be found in D6.1, with further information on the simulation setup in D6.2.

The implementation work that has been performed in WP6 will be made publicly available. Every relevant simulation framework part, i.e., SUMO, ns-3, and the iTETRIS framework has been open-source before the beginning of the TransAID project, and extensions written within TransAID will be released as an open-source package after TransAID’s completion as well⁴.

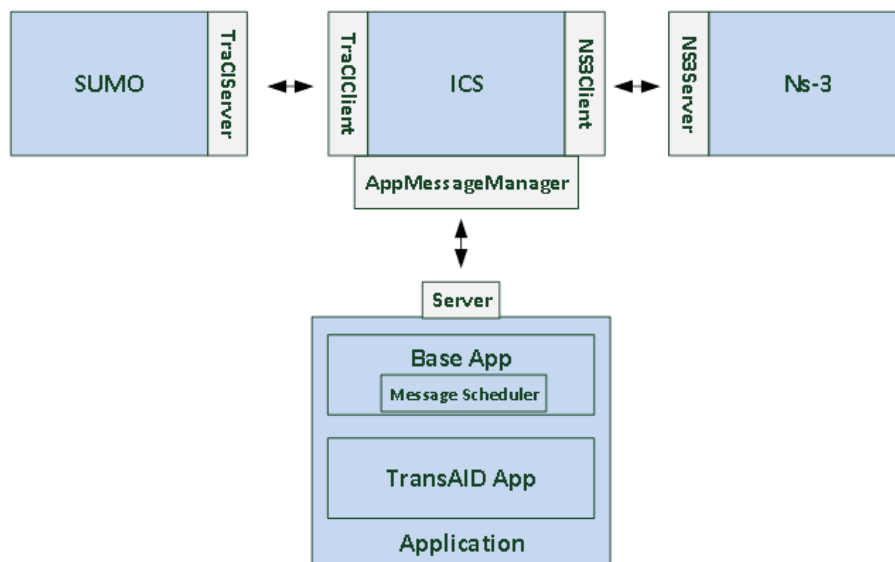


Figure 4: TransAID iTETRIS simulation framework

The investigation of the V2X communication’s impact on the proposed traffic management procedures revealed several findings. However, first as a verification step, the results were obtained for all use cases when employing ideal communication (i.e., no delayed or missing messages). The

⁴ At the time of writing, the method by which the work will be made available as open source has not been decided yet. Please check www.transaid.eu for further details.

results confirmed the statistical trends of the results from D4.2, where no V2X communication was considered. This reduces the likelihood of any deviations in the results due to implementation differences.

As for comparing ideal with realistic simulation of V2X communication, the simulation results in the project's first iteration for use cases 1.1 and 2.1 have shown that these scenarios are not adversely impacted by realistic V2X communication. Furthermore, use case 4.2 exhibited no significant impact of realistic communication on traffic KPIs for both urban and motorway traffic cases. However, in the motorway traffic case, a few single simulation runs have shown a sensitivity of the traffic management algorithm (in its current state) to communication errors, which might increase and turn significant for higher traffic demands and/or penetration rates than the ones considered here. Similarly, traffic KPI results for use case 5.1 suggest a certain sensitivity of the proposed traffic management measures to realistic V2X communication. For both traffic management algorithms, the origin of this sensitivity was traced to single, non-repeated transmissions of some infrastructure advice messages, which were not correctly received due to errors during wireless signal propagation. These flaws can be fixed by employing a transmission mechanism that ensures the correct reception of these infrastructure advices.

In the project's second iteration, the comparison of ideal with realistic simulation of V2X communication has shown that scenarios, in which traffic management procedures from the first iteration were complemented and/or improved upon (e.g., use cases 4.2 and 4.1+5.1), a higher robustness of the proposed traffic management measures to realistic V2X communication could be identified since, at least statistically, no negative impact of the realistic V2X communication on the respective traffic KPIs was observed. In addition, other scenarios and traffic management procedures considered in the second iteration were also found to be robust to realistic V2X communication. These findings were observed even despite the fact, that the level of service and traffic mix was increased in the second iteration.

Finally, in terms of simulation complexity, the realistic modelling and simulation of V2X communication was found to induce a significant computational overhead. Even though this was to be expected to some degree, some of the first iteration's simulation runs could not be run successfully until the end of the project due to the high complexity paired with technical/hardware problems. Thus, from a general perspective, a trade-off between computation time and degree of realism had to be made.

2.4.1 Discussion

The existence of a central Traffic Management Controller and its direct/robust connection to the RSUs were assumed such that this TMC could control and process all incoming and outgoing traffic of the RSUs without having to worry about potential connection issues between the RSUs and this TMC. Accounting for additional communication errors or transmission delays on these channels would have unnecessarily complicated the traffic management algorithms and simulations.

Likewise, positioning and communication radius of RSUs were assumed to be given a priori. In the real world, the positioning of RSUs must be made deliberately and would be dependent on the communication radius, among other parameters. In the same sense, parameters, such as time between subsequent transmissions of info messages (DENM), were assumed to have fixed values (e.g., 1 second). When implementing such scenarios in the real world, finding sensible values for these parameters is no trivial task and should also be made deliberately. It might even be a sensible choice to make these traffic-dependent and not use fixed values.

2.5 Real-world implementation

To validate the feasibility of measures and communications introduced in WP2 to WP6, WP7 implemented those in real-world demonstrators. The real-world implementation was done by performing three different feasibility assessments. Two of them have been performed on test tracks in Germany, and one on public roads in The Netherlands.

On the test tracks, several detailed tests of all scenarios have been performed, revealing that all traffic management measures could be successfully integrated and applied to automated vehicles in all use cases and scenarios. This includes the successful setup of the RSI and the automated vehicles.

In detail, the RSI included camera units, data processing units and V2X hardware. The image of a 2D camera was analysed and object detection and tracking has been performed. The resulting object list is forwarded to the roadside logic. In addition, also V2X messages received by the infrastructure are used. Considering both inputs, together with the road layout and the defined use case and scenario, the correct traffic management measure is calculated online. The resulting information and individual vehicle advice are sent out using proper V2X messages. In addition, a VMS is triggered to show respective signage.

On vehicle side, corresponding interfaces to the V2X unit have been implemented, which allow reception and sending of messages of different types. Furthermore, the automated driving software needed to be adapted to provide the required information and to process the incoming data. Special focus has been put on the reception of infrastructure advice (speed, lane, headway, ToC, and Safe Spot advice as well as path receptions) and on V2V cooperation using MCM. All parts could be successfully demonstrated in several scenarios.

In addition to the test track implementations, one use case was also performed on public roads: the merging assistant of use case 2.1. Here, a mobile setup has been used combining a camera for object tracking with induction loops on the highway and a V2X RSU. Considering the positions and speeds of the detected vehicles, a speed advice for the merging vehicle (a cooperative vehicle (CV) without automation capabilities) could be generated allowing the vehicle to successfully merge on the highway.

It was planned to showcase all developments to the public in two events, scheduled in Delft and Hannover. Due to COVID-19, both events had to be cancelled. Instead, videos of the tests have been created and a virtual testing meeting on the test track has been performed with all partners.

Therefore, and to enhance the development process, it was required that test drivers and public could understand what is currently happening in the system. A set of different HMIs showing the vehicle decisions, message receptions and advice implications have been implemented for the vehicles and the roadside. It must be noted that these HMIs are used for showcasing and debugging only.

In the following, the major findings of the tests are summarised.

Specific results for the individual use cases are:

Use case 1.1: Path information was provided to CAVs to circumvent road works via a bus lane. The area on the bus lane where driving was allowed was limited in its length. As the information was received before the CAVs reached the area, no TOR was initiated and the lane change to the bus lane was performed smoothly. Nevertheless, the range of the RSU plays an important role here. It needs to be assured that the information about the available path is received before the TOR is initiated to avoid human interaction. In the use case, the TOR was linked to DENM reception while the availability of the path was linked to reception of a MAPEM. As both messages have been sent by the same RSU, a TOR never happened. This of course can be different when testing at higher speeds,

or when the road works position is indicated in a digital map already before, e.g., by reception of a Radio Traffic Service/RDS-TMC.

Use case 1.3: Queue spillback at exit ramp. Here, the length of the area used as exit ramp is important. The CAV changes lane to the emergency lane as early as allowed, as this is the only way to reach its destination. If the spillback is long, it may conflict with the range of the RSU. In our tests on the test track, the RSU was placed further downstream. As result, the information that there is a spillback and that the emergency lane can be used was received partially late, resulting in sharp lane changes and sudden sharp braking manoeuvres. Therefore, it is mandatory that the range of the RSU(s) correlates to the spillback.

In addition, the test setup used in the car for this use case required the reception of both MAPEM and SPATEM to rate the MAPEM information as valid. As consequence, also a SPATEM had to be sent by the infrastructure showing an “always green” traffic light state on the emergency lane. Of course, this could be an artefact of the used system, but it should be mentioned that also other systems on the market could behave similarly, since currently both messages are mostly provided simultaneously, which is the normal situation at urban intersections. It should be highlighted in this context that the MAPEM offers much more than simple traffic light interaction.

Use case 2.1: A motorway merge area where CAVs are given speed advice to merge onto the motorway. In the public roads test performed in the project, only CVs have been used on the on-ramp. It could be shown that the speed advice led to smoother accelerations and that the gap could always be reached. Of course, a good and early vehicle tracking and a constant behaviour of the vehicles on the highway is key to a correct and useful early advice.

On the test track, CAVs have been used, on the on-ramp as well as on the highway. In a first iteration, infrastructure advice was given only and there were not any legacy vehicles on the road. As therefore all positions and speeds were known very precisely, the advice showed perfect results. In a second iteration, also legacy vehicles were included. In addition, the CAVs were able to use the V2V manoeuvre coordination in terms of MCM. All merging manoeuvres have been successfully demonstrated by using just this technique, since gaps were opened or lane changes were performed by the highway CAV “automatically”, while the on-ramp CAV “automatically” adjusted its speed accordingly.

Of course, this is only possible when there are CAVs on both parts of the road. If not, infrastructure is the only way to offer support. But infrastructure also plays an important role when there are more CAVs, as it can give an earlier advice. The reason for this is that the length of the planned and desired trajectories in the V2V MCMs are limited. The gap opening is not started before an overlap is detected between the desired trajectory of an on-ramp CAV and the planned trajectory of a highway CAV. Furthermore, infrastructure can trigger an early ToC advice to the on-ramp CAV in case the highway is blocked or an automated lane change most likely will not be possible. In this context, it would be beneficial if the infrastructure would know more details about the capabilities of the merging vehicle, or if the lane change advice could be linked to certain automation capabilities to avoid ToC advice when it is not needed.

Use case 2.3: Intersection handling due to incident. In the test track tests the used CAV was directly reacting to the blocked right-turn lane by changing to the left lane when the blockage information was received by DENM and the allowance to perform a right turn was received by MAPEM. Due to the communication range, this lane change is performed very early – even before the situation is recognizable by humans in the vehicle. This can possibly lead to a negative impact on traffic efficiency, as other behaviours like zipper merging should be preferred. In our tests, there have been no other vehicles on the left lane, so the results are fine. Nevertheless, the vehicle automation software should be able to distinguish whether an early lane change or a zipper merging should be preferred.

Use case 3.1: A merging situation where two two-lane motorways merge into one four-lane motorway. The idea is to harmonise traffic by assigning the outer lanes to AVs, thereby reducing close interactions between non-automated vehicles and AVs in the merging area.

In the test track trials, lane advice was given to the CAVs which was followed at all times.

Use case 4.2: A two-lane road with safe spots upstream of a road works zone on the left lane for CAVs to stop in case they reach the limit of their operational design domain. In this case the open right lane remains unblocked. In the test track trials, all messages could be realised. The automated vehicle drove on the right lane and executed the TOR as expected. When the MRM was initiated, the vehicle performed a lane change to the left and stopped. A good fine tuning was required to have the CAV leaving the right lane as fast as possible while also coming to a smooth stop in the relatively small safe spot. Besides, it has been found that the safe spot could be realised by two different parts of the MCM. On the one hand, the safe spot advice itself could be used, on the other hand also a combination of lane, speed and ToC advice could be used having a similar effect.

Use case 5.1 (standalone): A no-automated driving zone was simulated along the downstream part of a two-lane motorway. The zone can represent different situations (e.g., road works, geofences, weather, accidents, ...) that prevent AVs from staying in automated driving mode.

In terms of test track assessment this use case was very simple, as the infrastructure only needs to provide MCMs with ToC advice with different values to different CAVs. The vehicles reacted accordingly.

Use case 4.1+5.1 (combined): Distributed safe spots along an urban corridor. This combined use case has been tested on two test tracks separately, Peine-Eddesse and Griesheim. While the Peine-Eddesse tests focused on road side detection of safe spot occupancy and dynamic advice generation, the Griesheim tests focused on CAV reaction by comparing MCM, ToC and safe spot advice with reaction to DENM non-AD zone notification only (i.e., the Day-1 situation).

The Peine-Eddesse tests revealed that object detection is possible using a simple mono camera. Dynamic advice generation results in good behaviour of the vehicles. If the safe spot advice is received very shortly before the safe spot, the CAV sometimes cannot optimally plan the trajectory into the safe spot. As consequence, the CAV sometimes does not stop parallel to the main lane at the end. But still, the main lane is not blocked.

The Griesheim tests revealed that the Day-1 approach using DENM results far more often in a stop on the main lane as a safe spot could not be reached when the exact position of it is unknown. By using the MCM safe spot advice, the vehicle can much better plan the stop and lane change manoeuvres.

Tests in both locations revealed that the HMI in the vehicles and the behaviour of the vehicles, i.e., the optimal point for reducing the speed and the point when the ToC changes to an MRM, need to be investigated more closely. In terms of traffic efficiency, the CAV should keep its normal speed until it needs to brake for the safe spot manoeuvre. In terms of HMI, brake jerks or an early reduction of speed may be beneficial. In the tests in Peine-Eddesse, the vehicle softly decelerated (-0.5 m/s^2) when the ToC was initiated, and the MRM was started at the exact moment when the stronger braking (-2 m/s^2) for the safe spot started. In Griesheim, the vehicle was advised by the RSI to initiate a ToC at a given distance from the suggested safe spot in such a way for the driver to have enough time to take over. The suggested point to trigger a TOR is calculated by the RSI so that the vehicle arrives at the safe spot sufficiently after the ToC timeout expires). During the ToC timeout, the vehicle kept the current speed. When the timeout expired and the vehicle started an MRM, it decelerated to a low speed before the safe spot is reached and made a lane change and stop into it.

Common results for all the use case are:

All use cases have in common that a reduction of MRMs is possible by providing infrastructure advice. Such advice, and the availability of safe spots, clearly reduces the number of stopped vehicles blocking the road.

In some cases, the content of the exchanged messages is redundant:

- The MCM includes several data elements which are also included in the CAM but exchanged with higher frequency.
- The MCM safe spot advice may also be replaced by a combined ToC, speed, and lane advice, although having the safe spot advice separately may result in a different handling by the CAV.
- In some cases, the ToC can be trigger upon reception of a DENM (it is up to the receiver CAV implementer to decide if it is feasible, safe or meaningful to do it), but clearly an MCM ToC advice is more self-explanatory and accurate.

2.5.1 Discussion

The designed messages are suitable for enhancing CAV behaviour at Transition Areas. The feasibility could be shown in all use cases, the intended behaviour could be triggered at infrastructure and CAVs.

In some use cases, a closer investigation of the HMI and the exact behaviour of CAVs when performing ToCs and MRMs would be beneficial.

From a functionality point of view, when dealing with infrastructure-assisted ToC measures OEMs get new development challenges. I2V advices for distribution of ToC points and related safe spot suggestions might imply in worst cases that a CAV shall drive long distances in MRM (the driver has been proven not to be able to take over and the vehicle must reach the suggested safe spot). Moreover, for I2V ToC measures to optimally operate, OEMs should disclose implementation details like takeover lead times in different situations and operating conditions (by knowing these times, the RSI can better distribute ToC and calculate safe spot assignments). This especially is true for the ToC advice, which may be generated depending on the vehicle capabilities (e.g. in use case 2.1 and (4.1+5.1)). Another way of addressing this issue would be when the infrastructure relates its advices to specific restrictions, e.g., “perform a ToC when you are not able to handle situation X” or “perform a ToC when you only have camera sensors”. This of course would result in much more complex messages, so further investigation is required.

The variety of messages also gives opportunities for sensor data fusion in CAVs and the infrastructure. To get a complete overview, local sensor data needs to be fused with CAM data (at low frequency), MCM data, and received CPMs. Taking everything into account can largely benefit the precision of the sensor data fusion, and the range. Adding received meta data in those messages (e.g., plans, type of vehicle, etc.) can be used to further enhance planning at CAVs and advice generation at infrastructure.

In all cases, the processing time at infrastructure and vehicles plays an important role. Especially the generation of object lists using several sensors is a challenging task. In some systems it can take about 1s from the video image to the generated advice. As long as infrastructure advice is provided with a frequency of 1 Hz, this information is still sufficient. When adding more dynamic information, e.g., sudden blockages of safe spots or lane change advice at highway ramps, a high latency can result in the submission of an outdated advice. CAVs need to take this into account while planning their own movements. To allow CAVs to trust the received advice, a proper handling of generation times for all advices is required. In addition, CAVs always need to consider that a sudden emergency brake may be required, even when a good overview on the situation is received from the infrastructure.

In addition, also VMSs have been used to advise unequipped vehicles. In the project, the possibility of VMS recognition by the (C)AVs has not been in focus. It is expected that a VMS standardisation and related sign recognition could also benefit the handling of TAs, and possibly extend the range of countermeasures without requiring the extension of the range of electronic communication.

3 Gap analysis and recommendations

Currently there are few automated vehicles on the road, especially with higher levels of automation. Information regarding automation parameters, vehicle behaviour during ToCs and MRMs and traffic interaction in mixed traffic conditions, especially in transition areas, is therefore quite rare. Our research was supported by our OEM partner but nevertheless such information remains limited. The same can be said for information regarding legislation related to automated vehicles and the some of the cutting edge V2X message sets we used. Below we highlight some of the limitations of our research due to that limited information or due to pragmatic choices.

3.1 Behaviour of automated vehicles

There is limited information publicly available pertaining to the actual capabilities of highly automated driving systems (e.g., car-following, lane changing, gap acceptance, system parametrisation possibilities from the user's side). Besides the capabilities, knowledge about vehicle disengagements and relevant vehicle-driver unit behaviour in the context of real-world traffic is confined as well. Literature mainly reports findings from driving simulator studies. A publicly available dataset including information from testing on tracks and public roads would facilitate development of high accuracy and validity ToC/MRM models. Furthermore, data on interactions of manually driven vehicles with connected and automated traffic cannot be captured rudimentarily due to the low penetration rate of CAVs in the real-world fleet mix and the scarcity of relevant collected information. The implications of this fact on modelling and simulation activities and results can be profound.

3.2 Traffic management

Looking at the state of the art of traffic management, there remains a large theory-practice gap whereby only limited advancements are exploited in the field and artificial intelligence is currently mostly used as a building block. We concluded that there are quasi no (readily available) implementations of more advanced and/or generalised traffic management schemes that take higher degrees of vehicle automation into account. Most current research on this topic focuses on various aspects, such as solving partial problems/bottlenecks with specific measures (e.g., a new type of adaptive cruise-control, intersection management, a different kind of traffic light optimisation, creation of vehicle platoons, wireless communication to the driver/vehicle, etc.) and providing insight for the potential of autonomous vehicles in traffic management. All these solutions are very fine and usable; however, there are no experiments / setups whereby these solutions must come together to provide an answer to traffic management on a higher level, allowing the interplay between all the various solutions to lead to a better system performance.

An important gap in current modelling and legalisation, is how (C)AVs would/should react when (given) advice and/or actions conflict with traffic laws. With the real-time coordinated instructions of a TMC, (C)AVs should drive adequately during their journeys. However, it is necessary to concern to what extent such instructions should/can be made, especially when considering legal issues, i.e., whether traffic management should 'instruct' vehicles (and more specifically, automated ones) to force them into a situation in which they would be breaking the law. A possible way to resolve this dilemma is by having a classification of the traffic rules, distinguishing between types of rules as to whether they can be broken under specific circumstances. There are however numerous related issues that need to be dealt with, not in the least existing differences between countries' legislations. It is clear more input on this is needed, from both road authorities and OEMs.

Regarding the scope of traffic management systems and the related stakeholders, an open question still is how (N)RAs would position themselves in the traffic management chain. The latter concerns

the whole spectrum from individual vehicles on one end, over the fleets/OEMs, towards the infrastructure itself on the other end. What are relevant benefits for each of these parties, and who is willing to take liability, and/or pay up the required costs?

3.3 Capabilities of V2X

Cooperative perception has been shown to be an effective V2X communications solution to improve the perception capabilities of CAVs. In TransAID, we have considered highly accurate and reliable sensors to construct and generate CPM messages. Further work would be needed to account for sensing errors (in line with the current work of the C2C-CC) and the latency introduced by the sensors to generate abstract information of each detected object.

Regarding manoeuvre coordination based on V2X communications, there is limited information publicly available pertaining to the actual capabilities of highly automated driving systems to coordinate with other vehicles. These capabilities may differ between OEMs. On the other side, the role of the infrastructure to support manoeuvre coordination is being discussed at different levels. It is not clear yet to which extent the infrastructure will act as a virtual traffic agent or will just be restricted to provide advices to CAVs. When presenting the TransAID concept for manoeuvre coordination with infrastructure support, we have observed certain reluctances from OEM to enable the infrastructure to command vehicles to perform specific manoeuvres.

The study conducted in TransAID that combines DCC Access and DCC Facilities for the evaluation of cooperative perception is one of the most complete studies conducted to date. We demonstrated that the combination of DCC Facilities with DCC Access improves the effectiveness of the cooperative perception. However, DCC Facilities is still a draft standard and identified as optional. It is unknown whether it will become a mandatory component of the protocol stack. It is not clear if the DCC Facilities algorithm will be modified before its Technical Specification is approved. We will present our findings in the ETSI working group on this topic so that they can be considered.

In general, V2X communications solutions require to be incorporated into standards to be effectively deployed. That is the case for, for example, collective perception solutions, message generation rules for manoeuvre coordination, V2X message compression or broadcast acknowledgement mechanisms. However, in TransAID we have been intensively working to promote and disseminate all the proposed solutions in top-tier journals and international conferences, as well as in organisations like ETSI and C2C-CC.

Following current ETSI specifications, TransAID adopted the use of the ITS-G5 wireless technology, based on IEEE 802.11p. ETSI is now evolving the ITS communications architecture and specifications at different layers to enable the use of the LTE-V2X wireless technology. There are some initiatives in different regions of the world to adopt LTE-V2X instead of ITS-G5 for the support of V2X communication services. Future work could include not only the evaluation of LTE-V2X, but also its evolution 5G NR V2X (being designed by the 3GPP) and IEEE 802.11bd (evolution of IEEE 802.11p).

Finally, as briefly discussed in Section 2.4.1, there are various additional model and simulation parameters, especially related to V2X communication (e.g., channel load, latency etc.), which we had to make assumptions about since we do not know yet how these will turn out in a potential future real-world implementation of the scenarios.

3.4 Non-V2X communications

Regarding the communication to unequipped vehicles, more research is required. It is very difficult to forecast the developments of automated driving and its perception in the society. The key question

here is if automated vehicles will be recognised as perfectly integrated into traffic or if automated vehicles will per se be recognised as a special type of transportation. Taking into account the current developments, it may be the case that vehicles of specific companies are treated as “most likely driving automated” in some situations, possibly affecting the interaction with those vehicles. If the latter is the case, possible “misbehaviour” of the vehicles of any kind, including ToCs and MRMs, would be interpreted as an automation related artefact possibly not requiring an additional, e.g. visual, communication channel.

TransAID’s solution of having LED light strips at the back of automated vehicles will be beneficial in any case, but the exact content of such lights needs to be defined by performing more detailed analyses of such components. This goes to all external and dynamic HMI components of automated vehicles. In this light, it will be crucial to have an intuitive way of understanding the automation related additional information. One key question in this area is if driving with enabled automation should be indicated by an additional external light, and if so, where should this light be and what colour? For example, the colour blue was discussed already in the FP7 project HAVEit, although having an external blue light will conflict with emergency vehicles’ external lights.

Independent of the integration of automated vehicles and their appearance, it will be required to create additional road signs dealing with automated vehicles, at least showing that, e.g., an area is prohibited for automated vehicles or an area where only automated vehicles are allowed. The specific content and the exact message of such signs needs to be defined. This also goes into the direction of TAs in terms of dynamic infrastructure communication to unequipped vehicles.

In general, TransAID is a project dealing with technical solutions, but not focussing on HMI, user perception and legal aspects of road signs. As communication to unequipped vehicles is mostly a question of design, intuitiveness and regulation, more research is required.

3.5 Real-world implementation

Although the real-world implementations showed that all traffic management measures could be applied using the suggested message sets, it has to be mentioned that the implementation was done in a prototypic way. The development of related series products would require much more testing under real world conditions, which will be challenging at the current time since no highly automated vehicles are present on the roads. In addition, there is not much known about future behaviour and limitations of vehicle automations.

Nevertheless, it is very important to start the investigations at present times. As already described in Section 3.3, standardisation of messages is happening already now, and it was very important to include the role of the infrastructure at this stage.

The prototypic implementations showed that sensor fusion at the infrastructure becomes important. While simple mono cameras and induction loops are already suitable to perform object detection and tracking using currently available techniques, the processing time and the depending latency of advice generations are important factors.

To enhance infrastructure advice precision, the developed messages could be further optimised when path provision is not only done by using MAPEMs changing lane attributes, but also by including specific points on the roads which should be passed by CAVs individually. This could be done easily by the inclusion of such points in an additional MCM container.

In the same light, infrastructure advice could and should also be linked to CAV capabilities. The infrastructure advice done in TransAID is mostly individual, but the infrastructure does not have insights into specific individual CAV capabilities. Of course, the CAV may decide to not follow the advice if the system decides that the infrastructure rating of the situation, especially when sending a

ToC advice, was too conservative. But, currently there is no way (neither for infrastructure nor CAV) to make an informed decision given the information available in the advice. In the worst case, this could lead to a dismissal of all advices by the vehicles, making all countermeasures obsolete.

As previously stated (Section 2.5.1), Infra-assisted ToC distribution measures and safe spot suggestion can imply that a CAV shall drive long distances in MRM. This poses important questions for an OEM. Is it safer in such situation to drive at low speeds till reaching the suggested safe spot? Driving at low speed could allow a vehicle to better detect a closer safe spot, but at the same time driving at low speed can be a risk for faster surrounding traffic. Or is it better to keep the cruising speed till immediately before the suggested safe spot? In this case the risk for the surrounding traffic could be minimized, but it is questionable if an MRM should be executed at high speed.

As the HMI plays a major role in the recognition of CAV behaviour, and as the HMI was not part of the TransAID project, more efforts need to be taken to investigate optimal HMI strategies. This includes an internal HMI to the driver or passengers, but also an external HMI to surrounding traffic, as described before. In addition, the behaviour of CAVs while performing ToCs and MRMs needs to be investigated in more detail, focussing on the optimal point for changing from ToC to MRM and the related differences in the vehicle behaviour. Here, it is important to find the best match between warning the driver, warning the surrounding traffic participants, and traffic safety and efficiency.

4 Lessons learned

Having completed the work in work packages WP2 to WP7, there are several lessons learned. Some of these are mentioned in previous sections discussing the results or gaps in our approach. In addition, we look back on the process of the project itself and what we learned from that.

4.1 Behaviour of automated vehicles

Longitudinal motion of CAVs was explicitly simulated on the tactical level since ACC/CACC systems dictate the CAV actions (acceleration/deceleration) in the next time step according to the leading vehicle behaviour. However, simulation of a motion planning algorithm for CAVs would provide additional testing possibilities in the context of the TransAID simulation experiments, such as cooperative manoeuvring with the use of realistic communication protocols (desired/planned manoeuvres). Furthermore, decentralised cooperative lane changing was integrated in the traffic management plans of specific use cases (i.e., use case 4.2 urban/motorway, use case 2.3) and evaluated based on safety, traffic efficiency and environmental KPIs. Similar work for centralised cooperative lane changing would enable the comparison of the two approaches and provide insights in terms of their advantages and limitations.

Ultimately, evaluation of CAV vehicle-driver models and mixed traffic conditions in the context of simulation experiments that considered real-world road facilities and traffic conditions would enhance the overall validity of the simulation analysis.

4.2 Communications

V2X communications can support the traffic management messages defined in TransAID. This is particularly the case thanks to the definition and extension of V2X messages, the evolution/definition of efficient and reliable message generation rules, and reliability mechanisms that improve the system's scalability.

The conducted study has revealed that cooperative perception based on V2X messages is nearly ready to be standardised and deployed. This is particularly the case because the proposed solutions address the trade-off between channel efficiency and perception performance. We have assessed the scalability and utility of cooperative perception under a wide set of scenarios.

More work will be needed on manoeuvre coordination, given it is still at its early stages. In TransAID we have provided the basis for the decentralised and centralised coordination of vehicles, with the design of V2X message flows and generation rules. The obtained results show that reliable and accurate manoeuvre coordination is possible, but the channel load will need to be controlled effectively. Manoeuvre coordination requires the timely and reliable exchange of V2X messages, but current congestion control protocols may limit the transmission frequency of MCMs. This could thus affect the coordination time and further work will be required on this topic.

Future deployment of V2X systems to support advanced traffic management services will require a variety of messages to be exchanged with low latency and high reliability. In TransAID we have proposed different mechanisms to improve the reliability and scalability of the V2X message exchange. However, to cope with the transmission of Day-1, Day-2 and beyond V2X messages, multiple radio channels will be needed. The standardisation work to adapt current V2X communications and networking protocols has just started within ETSI through the STF 585, in which UMH is participating. To enable the use of multiple channels, changes in the ITS communications architecture as well as in the Facilities, Network and Transport, and Access layers will be needed.

Regarding the communication of TA related information from the roadside to the vehicles, flexibility and fast response to situations on the road are mandatory criteria. It is very important to assist traffic managers or even automate the full cycle from issue detection to traffic management measure creation to application on the road. V2X offers such flexibility and fast response, but also the communication to unequipped road users is of high importance when mixed traffic is considered.

Although vehicle automation is at its start, the negative impacts of TAs can only be avoided when specific countermeasures are initiated already now. This especially includes legal aspects like the definition of special signage for automated vehicles and their handling, as those aspects will take time. This also means signage at the roadside, including VMS content, and signage from automated vehicles to surrounding traffic.

4.2.1 Use case specific V2X communication aspects

From the simulations of the use-cases, it was noted that there are several lessons learned for various aspects of the scenarios, which should be, especially with respect to real-world implementation, kept in mind for future work. The relevant use-cases are mentioned for each lesson:

a) Road-side infrastructure

- (1.1, 2.1, 4.2) RSU locations should be chosen deliberately with respect to communication radius, communication delay, and the traffic management algorithm.
- (5.1) A trade-off between deployment costs and communication data redundancy should be considered.
- (1.1) The merge area should be chosen long enough for the timely reception of headway advice messages since CAM-based detection of vehicles on left lanes in the merge area leads to delays.

b) Automated vehicle control

- (1.1) CAVs currently change to the right-most (bus) lane as soon as the path info has been received which leads to congestion for high demands and penetration rates.
- (5.1) No-AD information is received by virtually all vehicles eventually to ensure a downward ToC before entry to the No-AD zone. However, it should be noted that immediate and complete compliance of CAVs with ToCs is assumed here. Possible compliance issues with these requests that might arise for future automated vehicles might heavily disrupt traffic behaviour.

c) RSU software

- (1.1, 4.2, 5.1) A central traffic management logic (TMC) is assumed which controls the RSUs. Therefore, a direct/wired connection to the physical RSUs is desirable.
- (1.1, 4.2, 5.1) CAM state information of vehicles should be estimated by TMC in case of missing timely state information. This is especially important in scenario 5.1. The current implementation takes this into account which adds to the robustness of the traffic management algorithm.

d) V2X implementation

- (1.1) The frequency of retransmission of the infrastructure advices should be further studied to guarantee the correct reception of the advices while keeping the channel load as low as possible to avoid negatively impacting the performance of V2X communications.
- (4.2) Techniques that assure the correct reception of infrastructure advices should be implemented for a more robust traffic management tolerant to sporadic communications failures.
- (5.1) Mechanisms guaranteeing the correct reception of infrastructure advices (such as acknowledgement communication packets (ACKs)) should be implemented for a more robust traffic management (as already discussed above).

- (5.1) Synchronous packet transmission by all RSUs assumes they are out of interference range requiring adequate RSU placement and/or the addition of a random back-off mechanism to reduce the interferences between RSUs.

4.3 Real-world implementation

As described before, all messages could be implemented successfully in the real-world in a prototypic way. All traffic management measures could be applied and a feasibility assessment of all use cases could be performed successfully. There are different lessons learned depending on the perspective/component:

Vehicle automation function design

A good link between automation function, especially decision making and trajectory planning, and communication unit is required to reach best possible results. The implementation on the Hyundai vehicle permitted HMETC to identify suitable and architectural solutions for V2X integration in a real automated driving platform. This was achieved by extending the integration successfully adopted during the H2020 MAVEN project in a backward compatible-way: the TransAID integration solutions and communication schemes were seamlessly added on the top of the MAVEN ones without compromising their functionality.

Running a real-world demonstration of a TransAID measure allowed having first-hand indications of the developments needed on the vehicle side when dealing with ToC and MRM-related suggestions V2X-received by the RSI. This includes design of OEM-specific strategies on the best way to react to infrastructure advices from an AD point of view in order to provide the most safety and comfort to CAV passengers. The experiences collected in this demonstration prepared the HMETC experts to have a more critical view when rating prototypical implementations made by the other TransAID partners.

Vehicle sensors and sensor data fusion

Like the automation function, also the sensor data fusion needs to be linked closely to the communication unit, as V2X offers a rising number of possibilities to enhance it.

HMI design

HMI plays a crucial role when designing ToCs and MRMs in the real world. This goes to internal HMI for the driver and passengers, but also for external HMI for surrounding traffic participants. Further studies need to be performed to find best solutions for HMI in both aspects.

Infrastructure sensors and sensor data fusion

Infrastructure should require technology to perform sensor data fusion. In the project, data was retrieved from multiple sets of induction loops as well as cameras. Mono cameras have been sufficient, but the usage of cameras is restricted, as GDPR must be applied. GDPR can result in down-sampling of image resolutions or online removal of faces/license plates. The fusion with V2X data is required to match received messages with local sensor data, which allows to specify which vehicle is being advised. Only with the augmented sensor data inputs, the infrastructure traffic management system can calculate (individual) advice for vehicles in the transition areas. For ideal advice generation, detection and continuous tracking of objects is required. To avoid latencies, the whole process of image generation, GDPR application, fusion, detection, and tracking needs to be fast, requiring high computer powers.

Infrastructure advice generation

The advice generation can only be as good as the sensors and sensor fusion allows it to be. In addition, it is highly dependent on the precision of the traffic management algorithm and its implementation. The better the data and data fusion model are, the better the result. While in practice, detailed sensor data from roads are often limited, TransAID real-world implementation utilised as much as possible the available infrastructure sensors: multiple sets of inductive loops to correct and augment vehicle data, especially in close to the transition areas. With only inductive loops data for use case 2.1, the infrastructure advice generation had a proof of concept pre-trial on public road, which has generated speed and lane advice to an equipped CV. Nonetheless, the precision of individual advice may not be sufficient for CAVs due to various reasons, such as different behaviours of CAVs, integration with CAVs, or the advice compliance rate of CAVs. Because the confidence level towards the infrastructure advice plays an important role in when vehicles consider the advice, thorough tests should be performed in the future for every scenario.

Real-world communication

Real world tests of the messages showed that communication ranges play an important role for planning of trajectories and manoeuvres. Especially the path provision needs to be enhanced in some circumstances, as the simple change of road attributes for certain areas (using MAPEM) results in the possibility to overcome specific situations. However, the way how this is achieved depends largely on the implementation of the vehicle automation function. Optimality from a traffic management point of view may only be achieved when more precise path information is provided, possibly by including individual way points.

In addition, MAPEM reception may be linked to SPATEM reception in some systems, as both messages frequently come together. Nevertheless, TransAID showed that the MAPEM itself contains further important information and should be forwarded to the vehicle automation function in any case.

4.4 The overall process of the project

Besides lessons learned regarding our study, there are also some lessons regarding the process of the project (i.e., the approach we chose) and the development of the use case implementations.

The selection of the final use cases took quite long. For a large part this was due to the limited availability of information regarding the possible issues in TAs and the behaviour of (C)AVs, specifically regarding ToC and MRM. This was true considering both literature as well as experts and stakeholders. In addition, it is unclear which penetration level of different vehicle types we can expect and to what extent those will support communications. As was reported in D2.1, there are many factors which affect TAs and the behaviour of vehicles in them. As a result, it took some time to determine which situations are suitable for studying TAs as well as how the simulations should be parameterised to cope with the multitude of combinations of factors.

In hindsight, we perhaps spent too much time on trying to find information regarding our ‘problem’ (i.e. mixed traffic in transition areas) and should have decided more quickly, it is what it is. Also, we recommend to use an approach similar to our vehicle mixes and traffic demand parameters to tackle the uncertainties regarding future penetration rates of automation and communication.

A quicker selection of the final use cases would have been more fruitful, as a lot of details and issues regarding the different cases would arise once implementation began, though the careful considerations beforehand were of value as well. By saving time, more resources could be spent on finetuning the simulations, resulting in more robust implementations and source code.

In similar spirit, adopting a more agile approach towards the implementation coding of the use cases into simulations would lead to faster release cycles on the one hand, and a better approach to mitigating any unexpected results on the other hand.

Closely related to the previous point is the fact that an a priori deeper understanding of the simulation logic behind the microscopic traffic simulator SUMO is a requirement. This is a prerequisite for dealing with at-first-sight anomalous results.

Furthermore, a more open and sharing approach should be followed on the EU level, but it is up to the EC to instigate programmes and opportunities (or even obligations) to exchange and align results between different projects. This would allow to compare the results and identify commonalities between the traffic management scenarios and (C)AV vehicle behaviour.

Splitting the work into two iterations might have been a good idea initially, but, at least for WP6, it turned out that a lot of the tedious tasks, especially porting the code from the Python scripts implemented in WP3 and WP4 to C++ code in WP6 with a very different code structure, had to be performed twice. Instead, focusing on about half the use cases with more features and improvements over time would have been much more motivating and would have been a better use of the same resources.

Another software related point is the choice of iTETRIS over alternatives for WP6. iTETRIS required spending a significant amount of time to perform a refactoring work of the iCS. It also required porting Python scripts developed in WP3 and WP4 to C++ while also having to adjust the code logic as needed for iTETRIS. While this might look like a problem solely related to TransAID, it can be argued that, from a user perspective, starting off with the traffic scenario (using SUMO) without communication seems very reasonable. The natural approach would then be to implement the traffic management algorithm and dynamically interact with the traffic simulation using SUMO's TraCI interface in the Python programming language since this language is the best supported one by TraCI. Another point in favour of Python is its advantage in rapid prototyping as an interpreted programming language. It is also important to note that the runtime, especially for higher levels of service and traffic mixes, was too high, resulting in very time-consuming debugging phases. Profiling has shown that a significant percentage (about half) of the CPU time is used by communication socket input/output operations. Note that this might be true for other coupling frameworks as well. Thus, there seems to be still room for optimisation of iTETRIS message passing between its core (iCS) and the coupled entities. Next time, it would also be very beneficial to look into a light-weight solution for V2X communication simulation that can be used with Python. This should prevent or at least alleviate some of the problems outlined above.

In terms of feasibility assessment, it would be helpful to get more insights into OEM developments. In this perspective, TransAID was happening very early, before several details of future (C)AV behaviour is known. The topic of ToCs, MRMs and TAs should also be more in focus of larger scale projects, which would allow broader testing, but also standardisation of countermeasures and the identification of further required additional message parts, like e.g., sharing of (C)AV capabilities.

In addition, the integration in existing traffic management centres would be beneficial to better address future topics like individual advice generation, but also to include more macroscopic strategies as possible countermeasures. Here, also scalability plays an important role, from larger communication ranges using range extension technologies (hopping, linking of RSUs) to advice generation on a street, local, regional or even a national level.

5 Link to other projects

Besides TransAID, there are many more initiatives that focus on various aspects that TransAID considered. Given the broad scope of aspects related to automated driving, the purpose of this chapter is to provide some links to other initiatives that go deeper into the aspects studied or approach them from a different angle. Additionally, it makes clear where in the research landscape TransAID is positioned.

5.1 Related to automated vehicle behaviour

Impact assessment of connected and automated driving (CAD) was conducted with the use of microscopic traffic simulation software in the context of the H2020 CoEXist research project. Vehicle models in VISSIM were parametrised to reflect different types of CAV driving logic (e.g. cautions, normal, all-knowing) and simulation experiments were run for different penetration rate of CAVs (Sukennik et al, 2018). Simulations results indicated that the introduction of CAVs might negatively affect traffic efficiency and safety unless automated functions of CAVs become sophisticated and can safely operate with safety margins comparable to those of human drivers (Olstam et al, 2020). Although similar findings were reported by TransAID, modelling of control transitions and minimum risk manoeuvres was out of the scope of CoEXist.

Work related to modelling human-vehicle interactions during control transitions was conducted in the context of the research programme Meaningful Human Control over Automated Driving Systems (Calvert & van Arem, 2020). A framework was developed to capture driver behaviour during control transitions based on existing theories that attempt to quantify complex human psychological processes (e.g. reaction time, situational awareness). Preliminary simulation results suggest that ToCs can induce traffic disruption (shockwaves) and are in compliance with similar findings reported by TransAID. However, there is limited practical evidence regarding the latter processes and the interactions between conventional traffic and AVs being in control transition state as stressed by both research efforts. Thus, preliminary simulation results should be assessed with consideration of current limitations pertaining to adopted mathematical methodologies.

Microscopic and sub-microscopic simulation software were used in the context of the INFRAMIX project to examine the performance of traffic control strategies accounting for AVs' presence in the fleet mix. For example, an ACC-based control strategy that adapts car-following headways of equipped and connected vehicles at bottleneck locations to improve traffic efficiency was evaluated with the use of microscopic traffic simulation (Lytrivis et al, 2020). Moreover, vehicle models (i.e. car-following and lane changing) developed for CAVs in SUMO by the TransAID team were also used by the INFRAMIX team to assess the impacts of AVs on traffic flow for various penetration rates. Similarly to TransAID findings, INFRAMIX simulation results showed that increased shares of AVs can have negative effects on traffic efficiency for specific parametrisation schemes of the vehicle models (Berrazouane et al, 2019). However, control transitions were beyond the scope of the INFRAMIX simulation studies.

Simulation studies focusing on the mobility and environmental performance of CAVs were also conducted by MAVEN and TOSCo projects (Blokpoel et al, 2018; Feng et al, 2019). The latter projects examined different Green Light Optimal Speed Advisory (GLOSA) systems that accounted for strings of CACC equipped vehicles and queues at traffic lights to enhance vehicle progression through signalised corridors and improve energy efficiency. Simulation experiments considering different road environments (low-speed and high-speed), traffic conditions (uncongested and congested), traffic signal plans (fixed-time, actuated, and adaptive), and initial conditions (vehicle speed and acceleration upon entrance to service activation zone, time point of vehicle entrance to service activation zone in the traffic signal cycle) were setup and executed. Simulation results showed

that GLOSA systems examined by MAVEN and TOSCo can significantly reduce number of stop events and improve energy efficiency. However, due to the specific scope of both projects (evaluation of C-ITS services for mobility and environmental benefits at signalised corridors) which did not encompass generic behaviour of CAVs or control transitions, the reported results are not directly comparable to those of TransAID.

5.2 Related to traffic management

Three main relevant projects that are closely related to our TransAID results are (i) L3Pilot, (ii) CoExist, and (iii) INFRAMIX. Even though concertation was set up with the latter two throughout the project's course, a closer link would be welcome. This enables us and them to directly compare the results (to the degree that this is possible). This comparison then needs to be made on two levels: on the one level we would look at the different scenarios and use cases that each project studied, and on the other level we would compare the specific outcomes of these where it is applicable.

A further investigation would lead us to outside projects that are grounded within the OEMs' own research. Vehicle manufacturers are also providing functionalities and are even – in close cooperation with fleet owners, or by providing this service themselves – taking a specific role as a stakeholder in the earlier mentioned traffic management chain.

Finally, a comparison could be drawn with, e.g., the TOSCo project from the US, albeit that this would be more on the level of individual (C)AV behaviour as not so much on the implementation and impact of the traffic management logic. However, similarly to many OEMs, it is also very difficult to obtain comparisons and collaborations here, as most of their results remain unknown due to their refraining from sharing many details (which is a consequence of working with a close group of OEMs).

5.3 Related to V2X communication

The definition of a message format for manoeuvre coordination has been addressed by different projects. AutoNET 2030 proposed a message designed specifically to allow lane change cooperation between vehicles. The MAVEN project designed a lane advice message that assists CAVs in choosing the optimal lane when approaching an intersection. In contrast, the IMAGINE project aimed at defining a scenario agnostic manoeuvre coordination concept. The TransAID project extended the concept defined by the IMAGINE project by allowing the infrastructure to have an active role in the coordination providing advices that increase the overall traffic safety and efficiency. The PAC-V2X project employs a similar strategy focusing only on the role of the infrastructure and providing complete trajectories to vehicles instead of general high-level advices.

Under TransAID, most of the work carried out on the analysis and improvement of the cooperative perception is incorporated and published in the ETSI Technical Report on collective perception (ETSI TR 103 562 V2.1.1). Also, the work carried out in TransAID on the DCC Facilities will be presented to ETSI, since its Technical Specification is not approved yet (ETSI TS 103 141).

TransAID has addressed the reliability of V2X messages using compression techniques that are aimed at reducing the interference and channel load. Other proposals can be found in the literature that pursue the same goal. One of the most relevant one is the DCC solution defined in ETSI TS 102 687 that is based on adapting the communication parameters (transmission power, message transmission rate, or data rate) to control the load. These proposals have shown to be effective to reduce the channel load but can influence the applications' effectiveness since they might affect, for instance, the communication range.

Current V2X communication technologies are incorporating mechanisms to enhance reliability of broadcast transmissions. V2X communications based on cellular technologies incorporate HARQ (Hybrid Automatic Repeat Request) (3GPP TS 38.213 V16.0.0). IEEE 802.11-based V2X technologies are also being revisited to support higher reliability for V2X broadcast transmission under the task group BD (Next Generation V2X). To this aim, MAC/PHY mechanisms developed over the past decade for 802.11n, 802.11ac, or 802.11ax are being studied. This includes the use of midambles for better channel estimation, advanced coding schemes, or congestion-based repetitions of the V2X broadcast messages. Discussions related to the use of acknowledgments for broadcast V2X messages are also ongoing under the task group BD. Therefore, TransAID's proposal can be relevant for this standardisation process.

5.4 Related to HMI and communication to unequipped vehicles

As TransAID on its own only touched HMI topics briefly in one task, research in other projects is very important. TransAID's work for internal HMI was based on former work of the H2020 project ADAS&me (see D7.2 for details).

Regarding communication to unequipped vehicles, TransAID linked itself to developments of VMS signage done in H2020 INFRAMIX as well as to road user communication and external HMIs as done in H2020 interACT.

5.5 Related to coupling traffic and V2X communication simulation

Even though iTETRIS has its benefits as an open-source framework for coupling traffic and V2X communication simulators, through the course of TransAID, we also found some limitations, as outlined in Section 4.5. In the literature, some alternatives can be found, which might be considered in the future (the following list is not exhaustive):

- Veins (Sommer et al., 2011) is an actively maintained open-source framework for vehicular network simulations and is focused on coupling the traffic simulator SUMO with the public-source communication simulator OMNeT++ (Varga et al., 2008). This framework is mainly written in C++.
- Eclipse MOSAIC (formerly “VSimRTI”) (Schünemann, 2011) is an open-source, multi-scale and multi-domain simulation framework written mainly in Java for the assessment of new solutions for connected and automated mobility. It is also actively maintained and allows coupling of SUMO with traffic simulators OMNeT++ or ns-3.
- Bieker et al. (2010) proposed a fast, approximating 802.11p simulation model for adding V2X communication to a traffic simulation. This should work easily with Python scripts already using SUMO's TraCI interface but it should be noted that this simulation of V2X communication is (deliberately) only an approximation of realistic communication.

5.6 Related to real-world prototyping

Real-world prototyping has been done using connected automated vehicles setup before project start and with knowledge from former and current European, international and national projects. TransAID's findings at the real-world prototyping will also influence ongoing and upcoming projects. Esp. the links to the following projects are important:

- EU FP7 HAVEit: Designs of ToCs and MRMs have been investigated largely in HAVEit, although V2X communication was not addressed at that time.
- EU H2020 MAVEN: Links to infrastructure support using communication esp. in terms of collective perception and individual advice at intersections. In TransAID, the developments have been taken into account esp. while developing the more general I2V-MCM. Furthermore, MAVEN developed procedures of virtual/augmented testing using hardware-in-the-loop techniques which have also been used in TransAID.
- EU H2020 ADAS&me: Design of ToCs and MRMs from a human centered perspective.
- EU H2020 INFRAMIX: Use of communication technology and dynamic influencing of traffic on public roads, including handling of road works areas. INFRAMIX is focusing on a general common advice to all CAVs, while TransAID focuses also on individual advice.
- EU H2020 L3Pilot: Testing and piloting of automated driving functions on a European level using standardized approaches.
- EU H2020 Hi-Drive: Dealing with fragmentation of Operational Design Domains and the requirements for continuous automated driving on public roads.
- US TOSCo: Traffic optimization for signalized corridors is researched and tested on public roads in this project using V2I communication.
- German Project KoMoDnext: Infrastructure support at intersections using collective perception (CPM), tested on public roads.
- German Project ViVre: Infrastructure-supported automated driving of public transport using collective perception (CPM) and infrastructure advice.

6 Conclusions

This document provides an analysis of the results of the TransAID project, its limitations and provides links to other initiatives to place it in context. In this final chapter we look back to the objectives set out at the start of the project and discuss to what extent those objectives were met.

The TransAID project formulated one main objective and divided that into seven sub-objectives. The main objective is:

To develop and demonstrate infrastructure-assisted traffic management procedures, protocols and guidelines for smooth coexistence between automated, connected and conventional vehicles especially at Transition Areas.

TransAID reached that objective, which is supported by the discussion of each of the sub-objectives.

Sub-objective 1: Evaluation and modelling of current automation prototypes and their drivers' behaviour.

As a first step, current automation approaches were investigated. In order to get a closer view on the undesired effects that may occur during highly automated driving and transitions, it was necessary to create a good understanding of the existing prototypes' behaviour, especially regarding how automated vehicles handle the transitions of control.

TransAID accomplished Sub-objective 1 via the development of vehicle and driver models that can emulate (C)AV longitudinal/lateral motion (i.e. ACC/CACC car-following, lane changing based on prototype (C)AV lane change behaviour), system-initiated downward control transitions and minimum risk manoeuvres (both in stop lanes or safe harbours). The latter models were integrated and tested in the microscopic traffic simulator SUMO. Moreover, the iterative TransAID project approach facilitated the refinement and enhancement of the (C)AV and control transition models (Section 2.1 and D3.1).

During the 2nd iteration, new (C)AV driver models were introduced and previous models were adapted to increase realism in reflecting (C)AV behaviour during lane changing and downward control transitions. A CACC model was used to replicate (C)AV car-following behaviour in the presence of V2X, while the previous parametrisation of the default SUMO lane change model was refined to better capture AV lane change behaviour, and the ToC model was extended so that it could emulate dynamical TOR triggering based on the prevailing traffic conditions. Additionally, an algorithm that explicitly enabled cooperative lane changing (including a decentralised approach) among CAVs via creation of safe gaps was introduced and tested (Section 2.1, D3.1 and D3.2).

Sub-objective 2: Assessment of the impact of Transition Areas on traffic safety and efficiency. Generate requirements on enhanced traffic management procedures.

The availability of models for highly automated vehicles allowed simulation and testing their behaviour under different transition scenarios. Such tests included varying proportions of different levels of automation and connectivity (see D2.2 and D3.1). The basic question was: how do the various existing systems influence each other and the traffic system at different levels of penetration? As a result, the impact of such systems in the areas where highly automated driving is possible or granted and during transitions was evaluated. Accordingly, the requirements for an enhanced traffic management system, as well as safety and efficiency metrics were formulated (D2.2).

TransAID also managed to accomplish Sub-objective 2 via the conduct of the baseline simulation analysis. Simulation experiments pertaining to Transition Areas identified by the TransAID project were executed for different traffic demand levels, traffic mixes, and parametrisations of the aforementioned vehicle/driver models. Simulation results yielded concrete findings with respect to

the effects of control transitions and minimum risk manoeuvres on traffic efficiency (Section 2.1 and D3.1). However, results remain inconclusive with respect to traffic safety. Thus, further analysis is warranted on the frontier of traffic safety which should encompass additional KPIs and increased model fidelity for traffic safety analysis. Moreover, it should be also noted that existing surrogate safety measures that were used in the context of traffic safety assessment, were explicitly developed and validated for conventional traffic. Thus, their interpretation should be handled cautiously when mixed traffic conditions are concerned.

The required traffic management measures are dependent on traffic conditions and the vehicle mix. In D2.2 and D4.1, requirements for the enhanced traffic management procedures are identified and translated into a where, when and how for traffic measures that seek to improve the local traffic situations from the baseline simulations. These requirements were then taken into the work that aimed to achieve sub-objective 3.

Sub-objective 3: Development of infrastructure-assisted management procedures and protocols to control connected, automated and conventional vehicles at Transition Areas.

In order to develop the most favourable traffic management system for Transition Areas, new simulations were conducted to test and validate various traffic management procedures according to the formulated requirements. The simulations included different use cases taking into account defined safety and efficiency metrics (see Section 2.2.2 and D4.2).

In WP2, use-cases were chosen through an extensive method. The use-cases could be distributed among five services (D2.1). The five distinguished services for TransAID are:

1. Prevent ToC/MRM by providing vehicle path information
2. Prevent ToC/MRM by providing speed, headway and/or lane advice
3. Prevent ToC/MRM by traffic separation
4. Manage MRM by guidance to safe spot (urban & motorway)
5. Distribute ToC/MRM by scheduling ToCs

In WP4 the chosen traffic management services were developed further, implemented and simulated based on the use cases selected (D2.2). The simulated scenarios are used and adapted from WP3. Various levels of scenario parameters like penetration of automation and communication, traffic demand levels and the lengths of the areas are considered.

The work done for TransAID's traffic management then naturally builds up to a more in-depth discussion of the selected services and use cases (five for the first iteration, and another five (updated) ones for the second iteration), each time highlighting when, where, and how traffic measures should be applied (Section 2.2.2 and D4.2).

Sub-objective 4: Definition of V2X message sets and communication protocols for the cooperation between connected/automated vehicles and the road infrastructure.

One of the biggest benefits of high automation is that the vehicles always generate local plans, manoeuvres and trajectories of their own progression. This data is available in each of the vehicles and does not have to be derived by interpreting human behaviour. For a traffic system as well as for individual connected vehicles, it will be valuable to get access to this data to some extent, while adhering to probable privacy issues.

Furthermore, highly automated vehicles as well as intelligent Road Side Units (RSUs), will be able to build a local dynamic map representing the surrounding situation, yet strictly limited to their own sensing capability (e.g., a vehicle will be able to detect only objects in the field of view of its sensors). Sharing individual sensory data with other vehicles and RSUs as well as trajectory plans and driving destinations will enhance the power of the automation in the car and the traffic management. V2X connectivity will allow to design cooperative driving manoeuvres so that automated and connected

vehicles can coordinate their driving to facilitate for smoother transitions. As a consequence, suitable V2X message sets and communication protocols were developed (Section 2.3.1, D5.1 and D5.2), which are able to support the above-mentioned functions and to communicate the traffic measures and the related control actions.

TransAID contributed to Sub-objective 4 with the definition of a complete message following the standardisation efforts at ETSI and extending the already existing standards when necessary taking into account the coexistence, interoperability and backwards compatibility. Another contribution to achieve this goal is the definition of the message flows for all the TransAID services that define the communications needed to implement the traffic management measures of the TransAID services (D5.2).

Two key messages to enable cooperative driving are the CPM and MCM that are currently being defined at ETSI. TransAID has extensively evaluated the current solution proposed by ETSI for the exchange of detected object information through CPM, and evolved it to improve its effectiveness and efficiency (Section 2.3.1 and D5.3). These results have been included in the ETSI TR 103 562. As part of the efforts that TransAID is devoting to contribute to the MCS, deliverable 5.2 has also performed an analysis of the generation rules for the MCM. The conducted analysis has highlighted the interest in utilizing dynamic MCM generation rules that take into account the vehicular context. To improve the cooperation between connected/automated vehicles and the road infrastructure, TransAID has also defined V2X solutions to improve the communications reliability (Section 2.3.1 and D5.3).

Sub-objective 5: Development of procedures to enhance the detection of conventional vehicles and obstacles on the roads and to inform/influence conventional vehicles.

In order to get a complete local dynamic map, it is crucial to recognise conventional vehicles and obstacles on the road, especially at times of mixed traffic with low penetration rates of connected vehicles. Infrastructure-mounted sensors like cameras can be used for detecting the positions and movement directions/speeds of those vehicles and obstacles (D5.2, D7.1 and D7.2). Also sensors mounted on each automated or connected vehicle can be used to enrich the granularity of the data or for validation when shared according to the last sub-objective. In addition, communication channels/methods for informing vehicles without V2X-equipment are mandatory for mixed traffic areas. As a first step variable message signs or traffic lights may be used for influencing those kinds of vehicles.

TransAID contributed to this objective with the exhaustive analysis performed about the impact of CPM generation rules in the communications channel load and the optimisation performed to the CPM generation rules that reduces the channel load while increasing the object awareness (D5.2). CPMs have been demonstrated to be a valuable solution to enable the detection of conventional vehicles and obstacles.

The sensor fusion algorithms included in Deliverable 5.2 (also discussed in D7.1 and D7.2) that enhance the detection of conventional vehicles and obstacles on the road contribute to the achievement of the sub-objective 5 of the project. TransAID investigated the most promising procedures of how and when each of these measures should be applied, and which granularity of sensors or informing devices are needed.

Deliverable 5.4 (and Section 2.3.2) discussed several options regarding how unequipped vehicles should be addressed when setting up future traffic management measures, esp. dealing with the introduction of automated vehicles in mixed traffic and the related limitations of such vehicles. After reviewing existing technologies to provide this information to unequipped vehicles, it was decided in TransAID that the project would focus on VMS, external HMI of a CAV and additional information provided on mobile devices individually (D5.4). These solutions were prototypically implemented

during WP7. The external HMI of CAVs is only implemented virtually, as HMI in general is not part of the TransAID project.

Sub-objective 6: Integration, test and evaluation of the TransAID infrastructure-assisted traffic management protocols and procedures in a simulation environment. Validation and demonstration of them by means of real-world prototypes at test sites.

The developed TransAID infrastructure-assisted traffic management protocols and procedures were integrated in an open-source Simulation platform based on SUMO, ns-3 and iTETRIS. This platform was then used to test and evaluate the protocols and procedures. In addition, the improvement of traffic safety and efficiency by following the TransAID approach was measured through various KPIs (D6.2).

In WP6 the simulations were extended towards greater realism through the modelling and implementation of the V2X communication processes necessarily involved in a real-world deployment of the proposed traffic management measures. This was done using the iTETRIS platform. The extended simulations consider individual messages and simulate their transmission and reception with a high level of detail (see D6.2 Section 2.2).

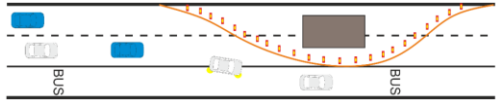
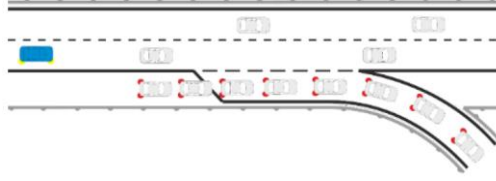
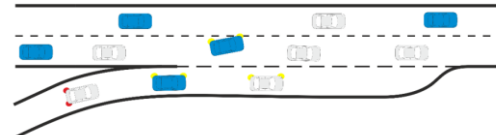

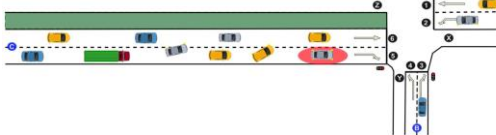
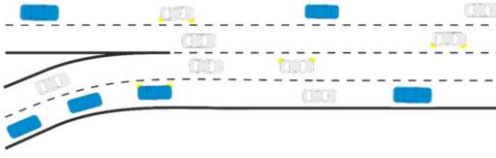
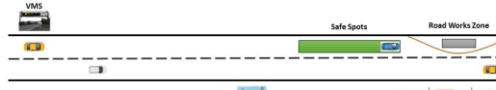
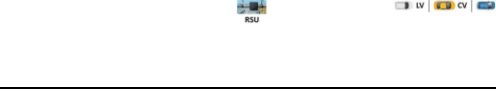
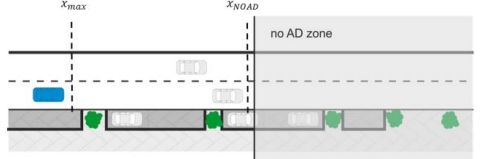
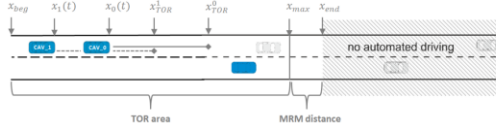
Where necessary, additional RSUs and detectors were added to the networks for retrieving information previously obtained directly from the simulation and for the spatial reference of participating nodes in the communication processes. The primary setup of the simulation platform is achieved within two phases. First, the traffic simulation including driver-and AV-models (WP3), and the simulation of connected vehicle communication (WP5) are coupled, adhering to the interfaces defined in D6.1. This yields the platform core. As a second step, the tools for the assessment of traffic safety and efficiency metrics and for the application of traffic management procedures are integrated into the platform (D6.2). The results are summarised in Table 1 (see below) for each of the selected use cases. Improvements for the indicated KPI (column name) are indicated by '+', a decrease by '-' and more or less no change by '~'. In addition, (U) stands for urban situations and (M) for motorway situations.

The feasibility of the developed management protocols and procedures was also tested in real world prototypes to get a closer view on details and technical pitfalls. The real-world implementation was done by performing three different feasibility assessments. Two of them have been performed on test tracks in Germany, and one on public roads in The Netherlands. On the test tracks, several detailed tests of all scenarios have been performed, revealing that all traffic management measures could be successfully integrated and applied to automated vehicles in all use cases and scenarios. This includes the successful setup of the RSI and the automated vehicles (Section 2.5 and D7.2).

Sub-objective 7: Provision of a guideline/roadmap to stakeholders regarding the requirements on traffic infrastructure and traffic management in order to cope with Transition Areas considering mixed traffic.

This final sub-objective is out of scope of this deliverable and specifically addressed in D8.3. At the time of writing that deliverable is being written and will provide guidelines and a roadmap for different stakeholders. Both the MANTRA (Kulmala, 2020) and EU EIP (Amelink, 2020) initiatives held surveys to determine the future actions that were deemed most important for the deployment of automated vehicles. In D8.3, after introducing TransAID and related concepts, we build upon those action by describing how TransAID had contributed to those actions and what should be done from the perspective gained through our research.

Table 1: Results of the simulations on the three KPIs

Use case	Efficiency	Safety	Emissions	Comments	Schematic overview of the use case
1.1	~	+	~	Safety critical events reduced by 45% to 70%, depending on LOS and traffic mix.	
1.3	+	+	+	For higher traffic intensities and a larger share of AVs, the effects diminish but are still positive. When the queue grows too large and vehicles stop on the main road, safety and efficiency are affected strongly.	
2.1 (1 st)	~	+	~	Large safety improvement and marginal improvements for both efficiency and emissions.	
2.1 (2 nd)	-	+	-	This use-case identified a clear trade-off between safety and throughput, depending on merging settings.	
2.3	+	+	+	As long as traffic remains stable all effects are positive, performance becomes worse on all KPIs when breakdown occurs, but still less severe compared to the baseline.	
3.1	~	-	~	Safety is severely affected due to increased number of cut-in lane-changes. Increased CAV share and cooperative manoeuvring seems promising to improve the results.	
4.2 (1 st)	~ (U) ~ (M)	~ (U) ~ (M)	~ (U) ~ (M)	Large safety improvements. Safety effects are smaller for a higher share of AVs and LOS.	
4.2 (2 nd)	~ (U) ~ (M)	~ (U) ~ (M)	~ (U) ~ (M)	Increased share of AVs and higher LOS diminish the safety effects, as expected.	
4.1 + 5.1	+	+	+	Large improvements on all measures. Higher traffic intensities result in relatively larger improvements.	
5.1	+	+	+	Large improvements on all aspects due to the smoothing of disturbances.	

7 References

For convenience and readability, the references are split into two sections. The first lists the relevant TransAID deliverables and where to find them. The second lists all external references.

7.1 TransAID documents

Below in Table 2, an overview is presented of all the deliverables of the TransAID project referenced in this deliverable. All the documents can be found on the website, with the exception of D7.1 which is confidential.

<https://www.transaid.eu/deliverables/>.

Table 2: Overview of TransAID deliverables

WP No.	Del. No.	Title	Release date
2	D2.1	Use cases and safety and efficiency metrics for smooth and safe traffic flow in Transition Areas	Jan-2018
2	D2.2	Scenario definitions and modelling requirements	Feb-2019
3	D3.1	Modelling, simulation and assessment of vehicle automations and automated vehicles' driver behaviour in mixed traffic	Sep-2020
3	D3.2	Cooperative manoeuvring in the presence of hierarchical traffic management	Feb-2020
4	D4.1	Overview of existing and enhanced traffic management procedures	Oct-2018
4	D4.2	Preliminary simulation and assessment of enhanced traffic management measures	Feb-2020
4	D4.3	Suitability and effectiveness study of traffic management strategies	May-2020
5	D5.1	Definition of V2X message sets	Aug-2019
5	D5.2	V2X-based cooperative sensing and driving in Transition Areas	Mar-2020
5	D5.3	Protocols for reliable V2X message exchange	Mar-2020
5	D5.4	Signalling for informing conventional vehicles	Mar-2020
6	D6.1	An integrated platform for the simulation and the assessment of traffic management procedures in Transition Areas	Oct-2018
6	D6.2	Assessment of traffic management procedures in Transition Areas	May-2019
7	D7.1	System architecture for real world vehicles and road side	Jun-2019
7	D7.2	System prototype demonstration	Jun-2019
8	D8.1	Stakeholder consultation report	Aug-2020

7.2 External references

Amditis, A. et al. (2019), Road Infrastructure taxonomy for connected and automated driving. In: Cooperative Intelligent Transport Systems, Towards high-level automated driving, IET, Chapter 14. p. 309-325.

Amelink, M., Kulmala, R., Jaaskelainen, J., Sacs, I., Narroway, S., Niculescu, M., Rey, Laura. and Alkim, T. (2020). Road map and action plan to facilitate automated driving on TEN road network, European ITS Platform (EU EIP), SA4.2.

Berrazouane, M., Tong, K., Solmaz, S., Kiers, M., & Erhart, J. (2019, November). Analysis and Initial Observations on Varying Penetration Rates of Automated Vehicles in Mixed Traffic Flow utilizing SUMO. In 2019 IEEE International Conference on Connected Vehicles and Expo (ICCVE) (pp. 1-7). IEEE.

Bieker, L., Krajzewicz, D., Röckl, M., & Capelle, H. (2010). Derivation of a fast, approximating 802.11p simulation model”, in Intelligent Transport Systems Telecommunications (ITST) 2010.

Blokpoeel, R., Zhang, X., Přikryl, J., Maia Pereira, A., Wesemeyer, D., Lücken, L., Harmenzon, M., & Boerma, S. (2018, December). Cooperative adaptive traffic light with automated vehicles. Deliverable 4.4, MAVEN Project (www.maven-its.eu).

Calvert, S. C., & van Arem, B. (2020). A generic multi-level framework for microscopic traffic simulation with automated vehicles in mixed traffic. Transportation Research Part C: Emerging Technologies, 110, 291-311.

European Research and Innovation Programme Horizon 2020 INFRAMIX project, Infrastructure Categorization, URL: <https://inframix.eu/infrastructure-categorization/>

Feng, Y., Florence, D., Balke, K., Leblanc, D., Wu, G., Adla, R., Guenther, H.-J., Shah, H., Moradi-Pari, E., Naes, T., Probert, N., Vijaya Kumar, V., Richard, W., Yoshida, H., Yumak, T., Deering, R., & Goudy, R. (2019, June). Traffic-level Simulation and Performance Analysis Report. TOSCo Project (<https://www.campllc.org/traffic-optimization-for-signalized-corridors-tosco-fhwa/>)

Kulmala, R., Ulrich, S., Penttinen, M., Rämä, P., Aigner, W., Carsten, O., Van der Tuin, M., Farah, H. and Appel, K. (2020). D5.2 Road map for developing road operator core business utilizing connectivity and automation, Making full use of Automation for National Transport and Road Authorities – NRA Core Business (MANTRA), D5.2.

Lytrivis, P., Manganiaris, S., Toetzel, D., Berghaeuser, G., Mischinger, M., Rudigier, M., Solmaz, S., Wimmer, Y., Pintsuk, A., Porcuna, D., Schrab, K., Protzmann, R., Doko, A., Markantonakis, V., Papamichail, I., & Papageorgiou, M. (2020, May). Evaluation, impact analysis and new safety performance criteria. Deliverable 5.3, INFRAMIX Project (www.inframix.eu)

Manganiaris, S. et al. (2019), D5.4 Infrastructure Classification Scheme, INFRAMIX project deliverable, URL: <https://www.inframix.eu/wp-content/uploads/D5.4-Infrastructure-Classification-Scheme.pdf>

Olstam, J., Johansson, F., Liu, C., Pereira, I., Fléchon, C., van den Bosch, F., Anvar, A., Miles, J., Sonnleitner, J., Tiberi, P., & Paliotto, A. (2020, April). Technical report on the application of the tools for assessing traffic impacts of automated vehicles. Deliverable 4.3, COEXIST Project (www.h2020-coexist.eu).

Rondinone M. *et al.* (2013), “iTETRIS: A modular simulation platform for the large scale evaluation of cooperative ITS applications,” *Simulation Modelling Practice and Theory*, vol. 34, pp. 99–125, May 2013, doi: 10.1016/j.simpat.2013.01.007.

Schünemann, B. (2011). V2X Simulation Runtime Infrastructure VSimRTI: An Assessment Tool to Design Smart Traffic Management Systems.” *Elsevier Computer Networks*, Volume 55, Issue 14, pp. 3189-3198, October 2011.

Sommer, C., German, R., & Dressler, F. (2011). Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis. *IEEE Transactions on Mobile Computing (TMC)*, vol. 10 (1), pp. 3-15, January 2011.

Sukennik, P. (2018). Micro-Simulation guide for automated vehicles - final. Deliverable 2.1, COEXIST Project (www.h2020-coexist.eu).

Varga, A., & Hornig, R. (2008). An overview of the OMNeT++ simulation environment. In *Proceedings of the 1st international conference on Simulation tools and techniques for communications, networks and systems & workshops (Simutools '08)*. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), pp. 1–10, 2008.