MAVEN

Managing Automated Vehicles Enhances Network

WP5: Enabling Technologies
Deliverable D5.2 ADAS functions and HD maps

Dissemination Level: PU

Version	Date	Release	Approval
01	20-07-2018	Michele Rondinone (HMETC)	Julian Schindler (DLR)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

Document Log

Version	Date	Comments	Name and Organisation
0.1	20-07-2018	First draft with proposed document structure	Michele Rondinone (HMETC)
0.2	23-07-2018	Second draft with proposed document structure and partners assignments	Michele Rondinone (HMETC)
0.3	10-08-2018	Inclusion of contributions from Dynniq in Section 2 and HMETC in Section1 and 4	Michele Rondinone (HMETC GmbH), Robbin Blokpoel (Dynniq)
0.4	13-08-2018	Inclusion of contributions from Dynniq in Section 3 and from DLR in Section 2, 3 and 4	Robbin Blokpoel (Dynniq), Julian Schindler (DLR)
0.5	17-08-2018	Included lessons learned from HMETC in Section 5	Dominik Matheis (HMETC)
0.6	22-08-2018	Further contributions from HMETC in Section 3 and from CTU in Section 4	Michele Rondinone (HMETC GmbH), Petr Bures (CTU)
0.7	28-08-2018	Inclusion of contributions from DLR in Section 3 and TomTom in Section 4 and Section 5	Julian Schindler, Andreas Leich, Hagen Saul (DLR) Morteza Damavandpeyma, Niels Finkenflugel (TomTom)
0.8	29-08-2018	Further Contributions in Section 5, final version ready for review	Damavandpeyma, Niels Finkenflugel (TomTom) Michele Rondinone, Thomas Walter (HMETC)
1.0	31-08-2018	Final modifications	Julian Schindler, Andreas Leich, Hagen Saul (DLR), Michele Rondinone (HMETC)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

Authors

No.	Beneficiary/Partner	Country
1	Julian Schindler (DLR)	Germany
1	Andreas Leich (DLR)	Germany
1	Hagen Saul (DLR)	Germany
1	Daniel Wesemeyer (DLR)	Germany
2	Robbin Blokpoel, Aleksander Czechowski (DYN)	The Netherlands
3	Michele Rondinone (HMETC)	Germany
3	Dominik Matheis (HMETC)	Germany
3	Thomas Walter (HMETC)	Germany
4	Petr Bures (CTU)	Czech Republic
5	Morteza Damavandpeyma, Niels Finkenflugel (TOMTOM)	The Netherlands

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

List of Acronyms and Terms

Acronym / term	Full name / description
5G PPP	5G Infrastructure Public Private Partnership
ACC	Adaptive Cruise Control
AD	Automated Driving
ADS	Automated Driving System
ADAS	Advanced Driver Assistance Systems
ANN	Artificial Neural Networks
C2C-CC	Car2Car Communication Consortium
C2X	Car to Anything
C-ACC	Cooperative Adaptive Cruise Control
CAM	Cooperative Awareness Message
CPM	Collective Perception Message
CEN	European Committee for Standardization
C-ITS	Cooperative Intelligent Transport Systems
DENM	Decentralized Environmental Notification Message
DGPS	Differential GPS
DMM	Decision Making Module
EC	European Commission
ETSI	European Telecommunications Standards Institute
EU	European Union
GIS	Geographic Information System
GDF	Geographic Data Files
GLR	Geographic Location Referencing
GNC	Guidance Navigation and Control
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
KPI	Key Performance Indicator

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

HAD	Highly Automated Driving
I2V	Vehicle to Infrastructure
ICRW	Intersection Collision Risk Warning
ID	Identifier
IMU	Inertial Measurement Unit
ISO	International Organization for Standardization
ITS	Intelligent Transport Systems
LAM	Lane Advice Message
LCRW	Longitudinal Collision Risk Warning
LSTM	Long-Short-Term-Memories
LR	Location Referencing
MAVEN	Managing Automated Vehicles Enhances Network
MRR	Medium Range Radar
NDS	Navigation Data Standard
OBU	On Board Unit
OEM	Original Equipment Manufacturer
OGC	Open Geospatial Consortium
QGIS	Quantum Geographic Information System
R2S	Road2Simulation
R&D	Research and Development
ROS	Robot Operating System
RSU	Roadside Unit
RTK	Real-Time Kinematic
SAE	Society of Automotive Engineers
SDO	Standard development Organization
SPaT	Signal Phase and Timing
SRR	Short Range Radar
TLC	Traffic Light Controller
TPEG	Transport Protocol Experts Group

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

UC	Use Case
UDP	User Datagram Protocol
ULR	Universal Location Referencing
VRU	Vulnerable Road User
VSE	Vehicle State Estimator
WP	Work Package

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

Table of Contents

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

List of Figures

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors’ view and the European Commission is not responsible for any use that may be made of the information it contains.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors’ view and the European Commission is not responsible for any use that may be made of the information it contains.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

List of Tables

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

Executive Summary

With the aim to achieve improved traffic safety and efficiency, the MAVEN project is developing traffic management algorithms at the infrastructure side for monitoring and coordinating cooperative automated vehicles (CAVs) at signalized intersections and corridors. Thanks to V2X communication, these algorithms exchange information with CAVs. CAV systems are in turn extended in the project with improved logic for consideration of the received V2X information in environmental perception and trajectory/manoeuvre planning modules. The MAVEN V2X information exchange allows CAVs to perform new driving functions suggested by the cooperative infrastructure (automated speed and/or lane change adaptations) as well as inter-vehicle coordination schemes like urban platooning. Nevertheless, not only V2X communication is needed by MAVEN to fulfil its goals. Other fundamental technologies shall be considered, extended and/or adapted to the needs of urban automated driving scenarios, and integrated in the overall system.

In this context, this deliverable describes the MAVEN project developments in terms of functions for protection of Vulnerable Road Users (VRUs) and CAVs' drivers, as well as for Highly Automated Driving (HAD) maps.

As explained throughout the document, the functions for protections of VRUs and CAVs' drivers are considered in the context of MAVEN as seamless integration of ADAS functions into CAV systems as well as extension of cooperative infrastructure algorithms to detect possibly dangerous situations and directly or indirectly influence CAVs' automated reactions. In this context, two main classes of functions have been considered:

- **Individual vehicle sensors data-assisted ADAS:** when detection, classification, risk assessment, and reaction rely on information achieved from different sensors of the ego-vehicle only, and
- **Cooperative sensor data-assisted ADAS:** when detection, classification, risk assessment, and reaction rely on V2X information received from other vehicles or infrastructure. To this class belong also some functions located at the infrastructure side whose operation directly or indirectly influences the AD behaviour.

The main results achieved are summarized as follows:

- For individual vehicle sensors data-assisted ADAS the following functions have been developed:
    - AD vehicle functionality for safe consideration of VRUs and obstacles with application for automated detection and reaction when turning at road intersections. This functionality reduces the risk of collision with VRUs by performing a threat assessment that considers objects detected and tracked by the sensor fusion and crossed with information about drivable lanes and planned route outputs. In parallel, it calculates a feasible manoeuvre and accordingly plans a vehicle reaction in terms of lane change, deceleration or braking.
    - AD vehicle functionality for safe handling of situations in which a non-cooperative manually driven vehicle tries to interfere in a platoon of MAVEN cooperative automated vehicles. This functionality allows safely managing such situations by estimating other vehicles' intention to change lane (by recognizing the indicator light setting, or a road topology with merging lanes) and reacts by controlling the safe distance at which a platoon vehicle should follow its preceding vehicle.
- For cooperative sensor data-assisted ADAS the following functions have been developed:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

- Improved CAV functionality for safe consideration of VRUs and obstacles, with application for automated detection and reaction when turning at road intersections based on vehicle-to-vehicle Collective Perception Message (CPM) receptions. This functionality extends the corresponding approach based only on individual vehicle sensors. In this case, the functionality allows for better (i.e. more timely) detection and reaction of VRU collision risk by considering CPM information in the threat assessment. As CPM can anticipate detection of objects not yet visible to the ego sensors, the limitations of non-cooperative approaches are overcome.
- Improved CAV functionality for safe consideration of VRUs and obstacles, with application for automated detection and reaction at road intersections based on CPM receptions from the cooperative infrastructure. This functionality reduces the collision risk by leveraging on object detection functionalities implemented at the infrastructure side. The infrastructure tracks VRU and vehicle trajectories and transmits CPMs. At the cooperative AD vehicle side, the received information is processed and provided to the tactical decision module to possibly apply soft reactions (like decelerations) as well as hard reactions (like braking).
- Cooperative intersection functionality for consideration of VRUs interfering with vehicles over an unprotected right turn. This functionality aims at increasing safety by reducing the probability of rear-end collision occurrences as a result of reducing the vehicles’ stops when arriving along a lane where other vehicles are queued waiting for a pedestrian to cross. This is achieved by detecting such conflicting situations via camera systems and triggering V2X lane change advices for incoming CAVs.
- Cooperative intersection functionality for limiting an uneven distribution of vehicles over parallel intersection-ingressing lanes. The safety advantage here is achieved by preventing large imbalance between parallel queues. This functionality detects uneven distributions thanks to various systems (including inductive loops and V2X receptions) and reacts by triggering V2X lane change advices for incoming CAVs.
- Cooperative intersection functionality for enhanced vehicle probing which supports the previous two functionalities. This new probing approach enhances original loop-based adaptive intersection control by relying on floating car data from MAVEN CAM extensions received from CAVs.

Regarding the HAD maps, the document describes the iterative evaluation process through which a suitable level of HAD map precision has been identified to support the MAVEN automated driving scenarios. For this purpose, commercially available HAD map databases of the designated test sites, provided by the MAVEN partner TomTom, have been considered. Based on these databases, the requirements for MAVEN vehicle automation in terms of HAD map format extensions have been identified. In particular, the project has detected the need of a “corridor” representation for road intersections as a pair of "virtual boundary lines" that connect the boundary lane markings of inbound lanes to boundary lane markings of outbound lanes. This information is necessary to AD SW system implementations because it indicates the boundaries to respect to perform a given intersection crossing manoeuvre without invading zones where conflicting situations can occur. With the MAVEN extensions embedded in the reference HAD maps, the MAVEN partners have performed an evaluation of the impact of the resulting HAD map accuracy on the AD vehicle trajectory and control calculation. By comparing the results obtained with the new MAVEN extended format with those obtained with the original format, this evaluation demonstrates that the resulting extended HAD maps are suitable for MAVEN automations as they permit trajectory calculation with sufficient quality.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors’ view and the European Commission is not responsible for any use that may be made of the information it contains.

As complementary activity, a thorough investigation of the state of the art on HAD map standardization is performed. This investigation permits identifying the minimum set of generic requirements for HAD maps, as well as a comparison with the adopted MAVEN HAD map format and extensions. As a result of this comparison, the MAVEN extensions in terms of intersection corridor approach are identified to be a possible input for standardization.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

1 Introduction

Highly and fully automated vehicles, especially when connected to the C-ITS infrastructure, can significantly contribute to meeting the EU objective of effectively accommodating growing mobility demands while still ensuring lower environmental impacts and increased road safety. An increase of driving automation functions in newly released car models is already a visible trend. Moreover, the deployment of C-ITS technology is about to start in 2019 [1]. The combination of automated driving and C-ITS is expected to be a key enabler for distributed coordination of highly automated vehicles [2][3], and will eventually permit the road infrastructure to monitor, support and orchestrate their movements.

In this context, the MAVEN project (Managing Automated Vehicles Enhances Network) will deliver C-ITS-assisted solutions for managing Cooperative Automated Vehicles (CAVs) at signalised intersections and intersection corridors with the aim of increasing traffic efficiency and safety. For this purpose, traffic management algorithms for inclusion and control of cooperative automated vehicles are developed at the infrastructure side. Thanks to V2X communications, these algorithms exchange information with cooperative automated vehicle systems that are in turn extended to include the V2X-received information into the logic of their environmental perception and trajectory/manoeuvre planning modules.

In order for the overall MAVEN system to fulfil its efficiency and safety goals not only V2X communications are needed. Other fundamental technologies shall be considered, extended and/or adapted to the needs of urban automated driving scenarios, and integrated in the system. From one side, current Advanced Driver Assistance Systems (ADAS) preventing and/or mitigating dangerous situations need to be seamlessly integrated in automated vehicle systems. Once integrated, they must be assessed in their capability to protect automated vehicles' drivers and Vulnerable Road Users (VRUs, e.g. pedestrians and/or cyclists), especially in those situations that are in scope for MAVEN (i.e. road intersections and intersection corridors). On the other side, these traditional ADAS functionalities can be extended thanks to the cooperative approach envisioned by MAVEN. Here, V2X communication will provide additional means for the detection of risks [4][5][6], hence overcoming the limitations of current detection systems or opening the door for less expensive sensor setups. As a result, in safety critical situations, the achieved information about VRUs and/or other obstacles will be used to better drive vehicle manoeuvre algorithms and infrastructure management policies. Another essential technology for automated driving in the MAVEN scenarios is the Highly Automated Driving (HAD) map. By providing a more detailed road network representation compared to traditional maps for navigation, HAD maps can support execution of automated driving planning and control schemes. However, current industrial HAD map formats fully support only representations of highway road networks and might not cover all the requirements of automated driving systems for representation of urban scenarios such as those considered by MAVEN. As planning and controlling algorithms are in general more challenging in urban scenarios (due to tighter curves, narrower lanes, etc.), they are more prone to imprecisions of HAD map databases. For these reasons, it is needed to investigate in MAVEN what is the level of completeness and accuracy needed by HAD maps to sufficiently support them.

1.1 Purpose of this document

The purpose of this document is to describe in detail the developments and evaluations performed in terms of ADAS functions and HAD maps for their correct inclusion in the overall MAVEN system and subsystems. As highlighted above, these developments are performed in such a way to comply with the requirement of driving automated in urban scenarios taking into account the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

presence of obstacles such as other vehicles or VRUs, especially in critical situations like crossing road intersections or during platooning applications. Regarding the work on ADAS, and following the MAVEN objectives, two classes of functionalities are in scope:

- **Individual vehicle sensors data-assisted ADAS:** when detection, classification, risk assessment, and reaction rely on information achieved from different sensors of the ego-vehicle only, and
- **Cooperative sensor data-assisted ADAS:** when detection, classification, risk assessment, and reaction are triggered and rely also on information received by other vehicles or infrastructure following the cooperative messages and collective perception approach described in Deliverable D5.1 [5]. As better explained in the following, to this class belong also some functions located at the infrastructure side whose operation indirectly influences the AD behaviour (e.g. lane change advice upon detection of potentially risky traffic situations).

Development of these functionalities and inclusion in the different MAVEN subsystems (i.e. cooperative automated vehicles and cooperative intersection) have been done by individual partners separately but in a compatible way[1], following the available means (e.g. limited availability of AD test vehicles) and expertise. This has permitted to obtain the highest number of solutions possible, hence better addressing the vast amount of real-life situations likely to occur in the reality. In this context, the following developments have been performed:

- For Individual vehicle sensors data-assisted ADAS:
  - HMETC has developed a functionality for safe consideration of VRUs and obstacles in its MAVEN AD SW architecture, with application for automated detection and reaction when turning at road intersections.
  - DLR has developed a functionality for safely handling situations in which a non-cooperative manually driven vehicle tries to interfere in a platoon of MAVEN cooperative automated vehicles.

- For cooperative sensor data-assisted ADAS:
  - HMETC has developed an improved functionality for safe consideration of VRUs and obstacles in its MAVEN AD SW architecture, with application for automated detection and reaction when turning at road intersections based on V2V receptions. As it will be explained in the following, this functionality enhances the performance of the individual vehicle sensors data-assisted approach.
  - DLR has developed a functionality for safe consideration of VRUs and obstacles in its MAVEN AD SW architecture, with application for automated detection and reaction at road intersections based on I2V receptions.
  - DLR has developed a functionality to provide VRU and obstacle information on the MAVEN infrastructure SW.
  - DLR has developed a functionality to provide lane change advices in its MAVEN intersection SW architecture in a coordinated way.
  - Dynniq has developed a functionality for consideration of VRUs interfering with vehicles over an unprotected right turn, integrated in its MAVEN intersection SW architecture. Application of this functionality is detection of a conflicting situation and

[1] Compatibility here is meant especially as the use of common V2X approaches [5][6], which constitute the main interface for interaction between systems developed by individual partners, as well as the adoption of the same implementation for the platooning algorithms [7].

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

reaction via triggering a lane change advice for incoming cooperative automated vehicles.

- Dynniq has developed a functionality for consideration of vehicles unevenly distributed over parallel intersection-ingressing lanes, integrated in its MAVEN intersection SW architecture. Application of this functionality is detection of the suboptimal situation and reaction via triggering a lane change advice for incoming cooperative automated vehicles.
- Dynniq has developed a functionality for enhanced vehicle probing integrated in its MAVEN Intersection SW architecture which supports the previous two functionalities. This new probing approach enhances original loop-based adaptive intersection control by relying on floating car data from MAVEN CAM message extensions received from CAVs.

In this document, these functionalities are detailed in terms of functional requirements, desired functional behaviour, evaluation scheme adopted and evaluation results.

Regarding the HAD maps, the document will describe the iterative evaluation process through which a suitable level of HAD map precision has been identified to support the MAVEN automated driving scenarios. For this purpose, the project partners have considered the MAVEN automated driving scenarios and identified the road network portions to be considered during evaluation. From the other side, commercially available HAD map formats (provided by the MAVEN partner TomTom) representing these road portions have been analysed. Availability of these map samples has permitted identifying on the one hand HAD map requirements for the MAVEN vehicle automation, and on the other hand an evaluation of the impact of the HAD map accuracy on the vehicle trajectory and control calculation. After incorporating the additions resulting from the MAVEN requirements in a new extended HAD map format, the same evaluation has been performed in a second iteration. As it will be shown in the following, the resulting extended HAD maps are suitable for MAVEN automations. As complementary activity, a thorough investigation of the state of the art on HAD map standardization has been performed. As it will be seen, this investigation has permitted identifying a minimum set of generic requirements for HAD maps and a comparison with the adopted MAVEN HAD map format and extensions. As a result of this comparison, the MAVEN extensions provide a novel intersection corridor approach that it is not yet considered and could be proposed for standardization.

1.2 Document structure

The rest of this document is organized as follows:

Section 2 gives an overview of the functional requirements needed for the development of the MAVEN functionalities for the protection of VRU and automated driving vehicle passengers, as well as for extensions of currently available HAD maps.

Section 3 describes the resulting ADAS functions developed individually by the involved MAVEN partners, including desired functional behaviour, adopted evaluation scheme and results.

Section 4 shows the MAVEN HAD extensions implemented based on the requirements identified in Section 3. In addition, the results of the automated driving evaluations and implementations performed with these extended formats are presented. Finally, a comparison between the extended MAVEN HAD map format and standard HAD map definitions is outlined.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

Section 5 highlights some lessons learned preliminarily or while implementing and testing the functions described in the previous sections.

Section 6 concludes the deliverable with some considerations on the results obtained and the future use of the developed schemes in the MAVEN integration and testing activities.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

2 MAVEN requirements

This section gives an overview of the functional requirements associated to the development of the MAVEN functionalities for the protection of vulnerable road users and automated driving vehicle passengers, as well for extensions of the currently available HAD maps. For deriving these requirements, the most relevant MAVEN use cases and scenarios affected by the development are described. The extracted requirements (in line with those specified in deliverable D2.2 [8] and referenced in WP6 and WP7 deliverables) are used as a justification for the targets of the ADAS functions and HAD maps extensions developed and tested as described in Section 3.

2.1 Requirements for protection of VRUs and AD vehicle passengers

To ensure protection of vulnerable road users and AD vehicles passengers, the objective of MAVEN is to develop innovative functions based on automated detection of- and reaction to possibly dangerous situations. It is here needed to specify that, although commonly referred to as Advanced Drivers Assistance Systems (ADAS), in the context of MAVEN cooperative automated driving (SAE Level 3-4) such functions are not assisting manual driving but are instead embedded as an integral part of the overall automated driving logic.

As defined in the introduction, two classes of functions have been set as MAVEN development targets in this regard:

1. **Individual vehicle sensors data-assisted ADAS**
2. **Cooperative sensor data-assisted ADAS**

The application of these functions has been envisioned in some of the MAVEN use cases described in the deliverable D2.1 [4], in particular UC8 and UC16. In the following, these use cases' scenarios, where the above mentioned functions are applied, are briefly reminded. This allows listing a set of requirements that are taken as reference for the developments and testing results illustrated in Section 3.

2.1.1 Individual vehicle sensors data-assisted ADAS

These functions are applied to the following use cases' scenarios:

UC 16, scenario 1: **VRU/obstacle consideration at intersection based on on-board sensors**

In this scenario, cooperative automated vehicles are approaching, from different directions, an intersection where a pedestrian is currently in a dangerous situation (as its position and heading is possibly conflicting with the planned trajectory of one or more automated vehicles). The VRU is visible only by some of the vehicles approaching. The other vehicles cannot detect the VRU (e.g. because behind the corner) and could hit him if no automated vehicle reaction based on on-board sensors is taken. As a consequence this scenario is meant to demonstrate the following functions:

- Detection with local sensors (close to series for the Hyundai AD vehicle)
- Reaction on AD (steering/braking) based on assessed risk
- Reaction on V2X by Collective Perception Message (CPM [5]) transmission of detected objects after assessing convenience

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

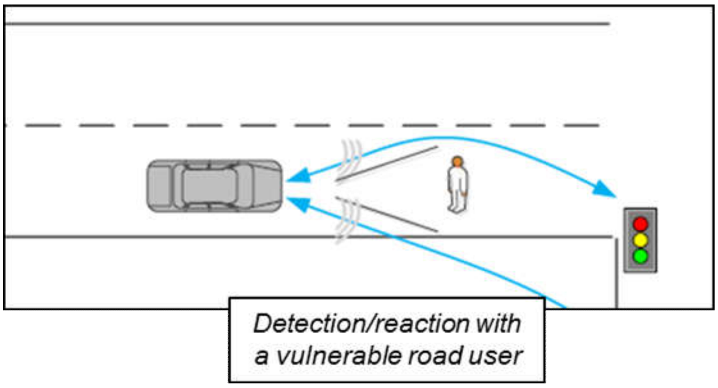

Figure 1: VRU/obstacle consideration at intersection based on on-board sensors

The functional requirements to be verified by the development results highlighted in Section 3 are the following:

- Object of VRU size detected with local sensors
- Object classified as VRU
- VRU object forwarded to AD decision modules
- AD reaction to evade or brake to full stop
- Vehicle stops or evades before hitting the VRU
- VRU object forwarded to CPM generation unit
- CPM generated and sent via V2X

UC 16, scenario 2: **Handling non-cooperative vehicle interfering with platooning AD vehicles**

In this scenario, a platoon is driving on an urban two-lanes road. A non-equipped vehicle driving on the other lane needs to change the lane. It is starting to indicate this and requires that the platoon opens up a gap. This scenario is one of the key scenarios for platooning safety in general, and especially for urban platooning, where lane changes and the need to turn occur very often. Cooperative behaviour with non-equipped vehicles is mandatory for the introduction of platoon systems, as people sitting in the non-cooperative vehicles will get in direct contact with those vehicles and build their AD user acceptance based on the perceived safety of that experience. Nevertheless, this breaking up can be considered as special situation for platoons. It is important to mention that platoon break up scenarios are difficult to detect, as the vehicles are driving close to each other, reducing the field of view of the camera responsible for the detection of the indicator signal. In addition, it is more likely that vehicles driving behind will detect the indication, but vehicles in front (e.g. the platoon leader) possibly have to take action. Therefore, the detecting vehicle has to forward this information to the other vehicles driving in front. As a consequence, this scenario is meant to demonstrate the following functions:

- Detection with local sensors (at platoon follower vehicles)
- Reaction on platoon logic (platooning break-up)
- V2X reaction by CPM transmission of detected vehicle

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

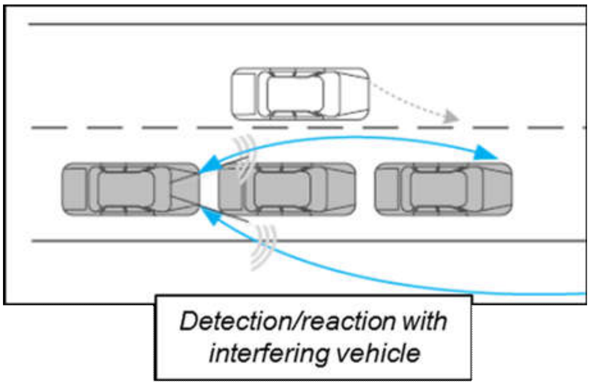

Figure 2: Handling non-cooperative vehicle interfering with platooning AD vehicles

The functional requirements to be verified by the development results highlighted in Section 3 are the following:

- Camera located at a platoon follower vehicle detects vehicle on platoon's adjacent lane
- Camera detects indicator signal of this vehicle
- Sensor data interpretation unit rates vehicle intention to change lane to the platooning lane
- Vehicle intention is forwarded to platoon logic
- Platoon logic triggers platoon break-up
- AD software reacts to platoon break-up command by opening a gap between the platoon members
- Object data is forwarded to CPM generation unit
- CPM generated and sent via V2X

2.1.2 Cooperative sensor data-assisted ADAS

These functions are applied to the following use cases' scenarios:

UC 16, scenario 1: VRU/obstacle consideration at intersection based on CPM receptions from vehicles

In this scenario (Figure 3), cooperative automated vehicles are approaching, from different directions, an intersection where a pedestrian is currently in a dangerous situation (as its position and heading is possibly conflicting with the planned trajectory of one or more automated vehicles). The VRU is visible only by some of the vehicles approaching. The other vehicles cannot detect the VRU (e.g. behind the corner) and could hit him if no automated vehicle reaction is taken. Nevertheless these vehicles get informed in advance about the presence of the VRU thanks to the reception of CPM messages from the detecting vehicles. This information is used to influence automated driving algorithms on the receiving vehicles (e.g. decelerating/stopping). As a consequence, this scenario is meant to demonstrate the following functions:

- Detection with V2X CPM receptions from other vehicles
- Reaction on AD path planning algorithms (early consideration in perception module of objects that cannot be detected via local sensors yet)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

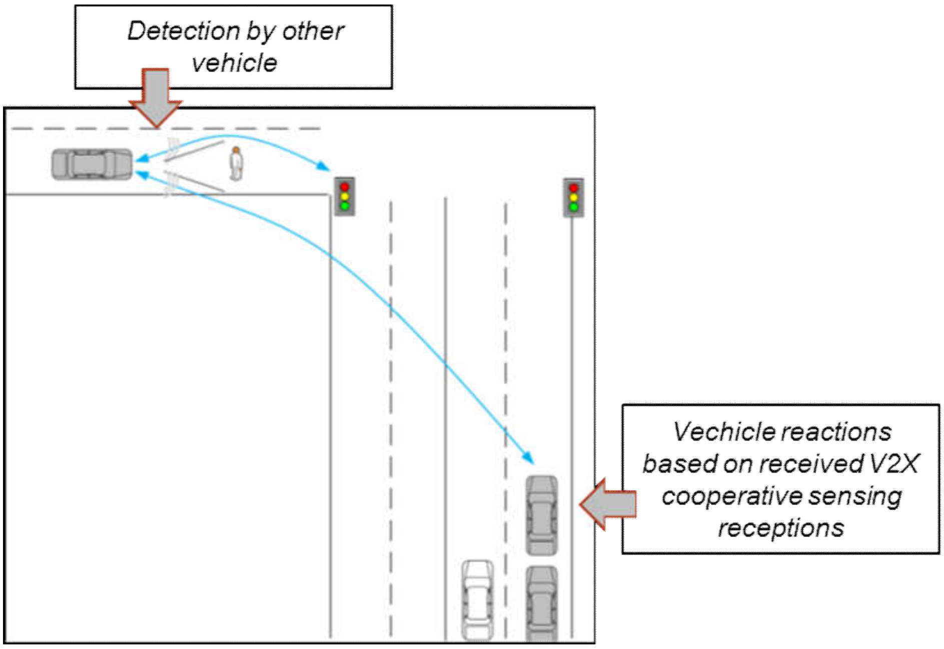

Figure 3: VRU/obstacle consideration at intersection based on CPM receptions from vehicles

The functional requirements to be verified by the development results highlighted in Section 3 are the following:

- Vehicles receive CPMs from other vehicles
- Sensor data fusion generates consolidated model of the vehicle environment, e.g. by using multi-tracking methods.
- Consolidated model forwarded to AD decision modules
- Consolidated model is used as an input to threat assessment in decision modules
- AD reaction on path planning algorithms is executed if threat assessment detects a risk: the vehicle shall decelerate till the threat is confirmed by inputs from local sensors.

UC 16, scenario 3 and UC9 scenario 2: **VRU/obstacle consideration at intersection based on CPM receptions from infrastructure**

This scenario differs from UC16, scenario1 in terms of source of CPM generation. While in scenario 1 the CPM is generated by another vehicle, here it is generated by the infrastructure. Therefore, the data flow is also slightly different. First of all, the infrastructure needs to be equipped with detection (and if possible tracking) devices for VRUs (pedestrians and bicyclists in this case) and vehicles. In MAVEN, this is done by special cameras, like hemispherical cameras. The images of the camera(s) are processed, objects are generated and classified. In addition, some systems allow tracking of objects and calculation of speeds and even trajectories.
By using camera parameters and the list of detected objects, the generation of CPMs is possible. The CPMs are broadcasted by RSUs and received by the MAVEN vehicles in the same way as depicted in UC16, scenario 1. The information is again used to influence automated driving

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

algorithms on the receiving vehicles (e.g. decelerating/stopping). As a consequence, this scenario is meant to demonstrate the following functions

- Detection and classification of vehicles and VRUs (Pedestrian and Bicyclist) on the infrastructure side
- Communication of both via CPM
- Reaction on AD path planning algorithms (early consideration in perception module of objects that cannot be detected via local sensors yet)

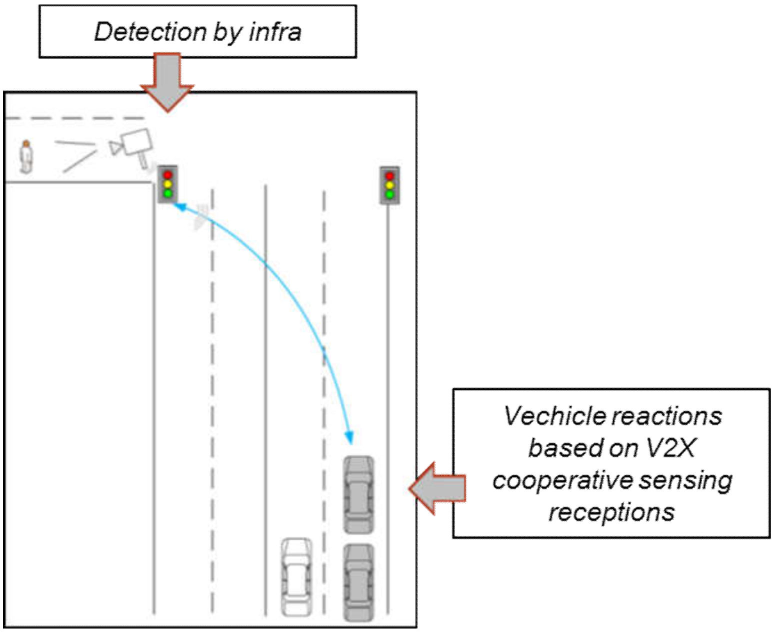

Figure 4: VRU/obstacle consideration at intersection based on CPM receptions from infrastructure

The functional requirements to be verified by the development results highlighted in Section 3 are the following:

- Infrastructure detects and classifies vehicles and VRUs (Pedestrian and Bicyclist)
- CPMs are generated containing the detector parameters and the list of objects
- CPMs are sent via the RSU
- Vehicles receive CPMs from infrastructure
- Sensor data fusion generates consolidated model of the vehicle environment, e.g. by using multi-tracking methods.
- Consolidated model forwarded to AD decision modules
- Consolidated model is used as an input to threat assessment in decision modules
- Reaction on AD path planning algorithms (early consideration in perception module of objects that cannot be detected via local sensors yet)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

UC 8, scenario 1: Lane advice when VRU is detected to interfere with unprotected right turn using LAM message

The scenario is illustrated in Figure 5 and follows these steps:

- Pedestrian having right of way over an unprotected right turn is detected. This would require right-turning vehicles to yield.
- When sensors are available, the presence of waiting vehicles should be detected.
- Since all vehicles on this lane, including the ones going straight have to wait, this can cause a significant spillback on the rightmost lane of the east-west direction in Figure 5.
- The grey vehicle is approaching the intersection and still has the opportunity to change lanes. Therefore the infrastructure sends a lane advice message (LAM [5]) to that vehicle (detected via CAM receptions [5]) to change lanes and pass a (potential) queue.

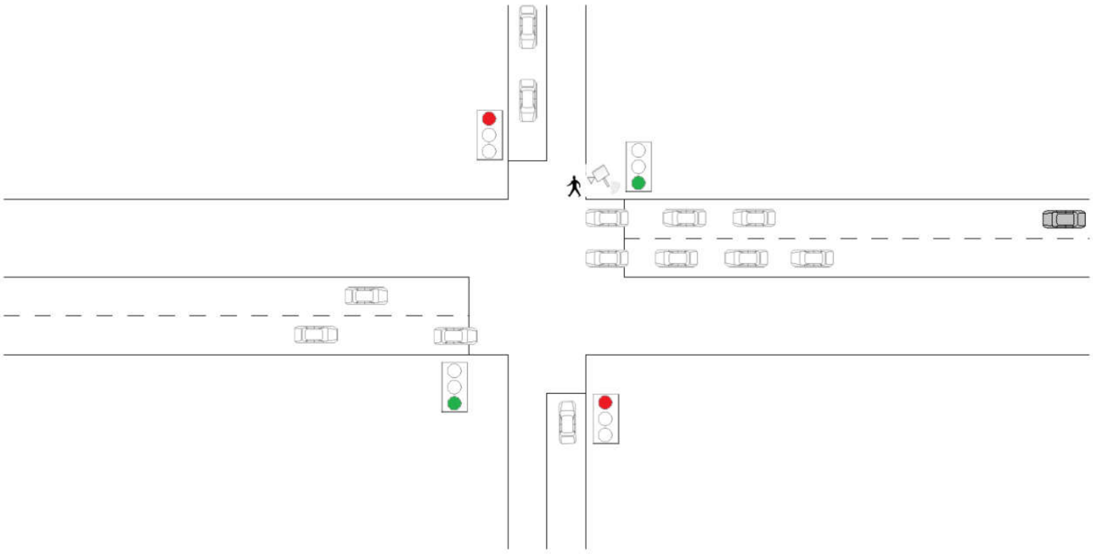

Figure 5: Lane advice for roads with unprotected right turns

It should be noted that the direct safety aspects for the conflict between the VRU and the right turning vehicle are not part of this scenario. Safety warnings, for example using DENM were extensively researched by the XCYCLE project [9] and sharing the perception is part of UC 16 in MAVEN.

This scenario has several requirements of which some are optional:

- VRU detection sensors are required to detect the presence of VRUs on the conflict area. The sensors can also cover the area before the conflict to add predictive elements.
- An RSU has to be present to capture CAMs from vehicles and transmit LAMs.
- Connection from the RSU to the traffic light controller to acquire data of current traffic light status. This is essential to identify whether a conflict occur.
- Automated vehicles have to indicate their intended direction using the MAVEN CAM extensions [5]. This is required to provide lane advices that do not impede the vehicle to follow its intended path.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

- Optional are sensors to track vehicle movements to detect whether there is a vehicle that wants to turn right and therefore needs to stop. If this sensor is not present, historical turning percentages will be used to estimate the occurrence of the queue formation.

UC 8, scenario 2: Lane advice for queue distribution at signalized intersections

The scenario is illustrated in Figure 6 and follows these steps:

- Infrastructure sensors detect a longer queue at the outer (rightmost) lane of the east-west approach.
- The grey vehicles are approaching the intersection and still have the opportunity to change lanes.
- The infrastructure sends a lane advice to those approaching vehicles to change lanes with the aim of distributing traffic evenly over the lanes.

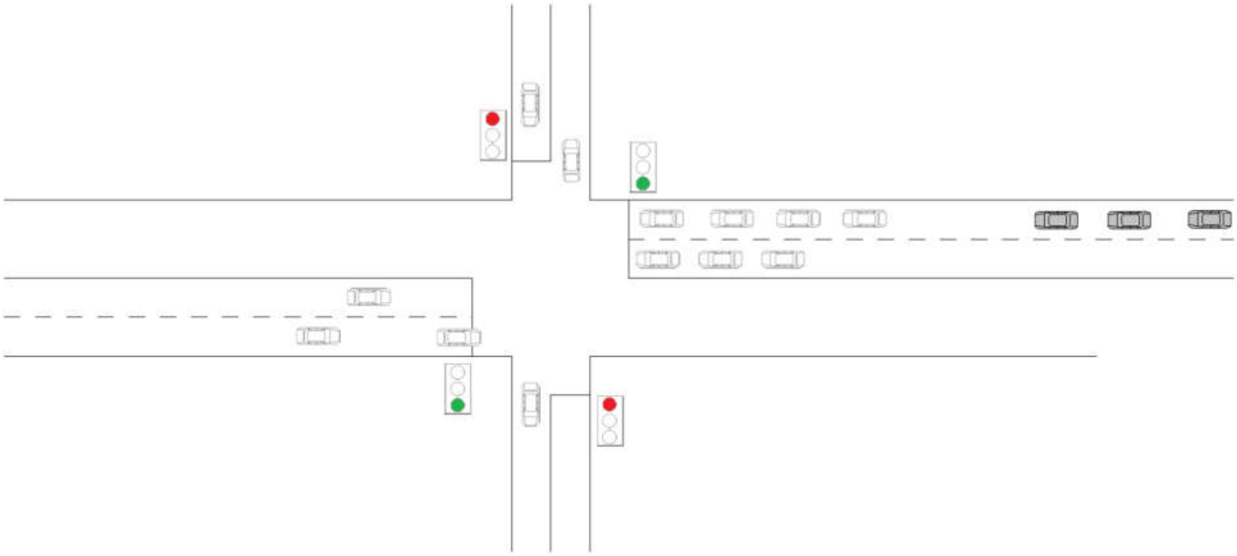

Figure 6: Lane advice for efficient queue distribution

The requirements for this scenario are as follows:

- The infrastructure requires a sensor that can measure speed and position of waiting and approaching vehicles over a distance of at least 150 meters. This enables the infrastructure to measure non-cooperative vehicles as well, which is essential for the optimization objective of the use case.
- Automated vehicles have to indicate their intended direction using the MAVEN CAM extensions. This is required to provide lane advices that do not impede the vehicle to follow its intended path.
- An RSU has to be present to capture CAMs from vehicles and transmit LAM.
- Connection from the RSU to the traffic light controller to acquire data of current traffic light status. This is essential to predict the evolution of the queue, e.g. if a queue has been dissolved by the time the vehicles arrive at the intersection.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

2.2 Requirements for Intersection control enhancement by vehicle probing

Additionally to requirements for the mentioned ADAS functions, this section also reports the requirements for Intersection control enhancement by vehicle probing. This functionality is necessary for the operation of the infrastructure-based developments presented in Section 3.3, and therefore the associated requirements are reported here for better understanding.
In D5.1 [5] CAM extensions were presented to provide extra information to the infrastructure. This information has been fed to the traffic control algorithm to isolate the benefits of this information. In D2.1 [4] this was described under UC15 scenario 1, single vehicle approaching cooperative traffic light, which can be briefly summarized with the following steps:

- A vehicle approaches a traffic light and transmits MAVEN extended CAMs with intended turn direction information included.
- RSU receives and decodes the extended CAM, map-matches the vehicle, i.e. determines the distance to the stop line.
- RSU writes the data to the traffic control algorithm.
- Traffic control algorithm fuses the data with its queue model based on infrastructure sensors.
- Traffic control algorithm recalculates the optimal control plan.

The functional requirements for this scenario are as follows:

- Automated vehicles have to indicate their intended direction using the MAVEN CAM extensions.
- An RSU has to be present to capture CAM and transmit LAM.
- Connection from the RSU to the traffic light controller to submit the data about detected vehicles.
- The traffic control algorithm has to be adaptive and uses queue models to incorporate the information in its optimization process.

It should be noted that other V2I and I2V information has strong algorithmic components with regards to the queue models that were developed in WP4 and are therefore reported in D4.1 [10] or will be reported in D4.3, when submitted. The effort in WP5 focussed on isolating the benefits of the intended turn direction in the MAVEN CAM extensions for control performance.

2.3 Requirements for HAD maps

HAD maps provide a precise and detailed description of the road characteristics (e.g. lane and curb positions, etc.) along with updatable information (variable speed limits, closed lanes, etc.). As a consequence, automated driving algorithms have more precise inputs to implement driving control schemes. In this context, the MAVEN partners have investigated the use of HAD maps for the MAVEN automated driving scenarios starting from commercially available solutions (provided by the MAVEN partner TomTom) and identifying, in an iterative evaluation process, which level of precision HAD maps need to support by increasing levels of information/precision for subsequent evaluation steps. The TomTom HAD Map is a highly accurate and realistic representation of the roadway, including the following map features/attributes like 3D geometries of lane centrelines, lane dividers, road borders, and guard rails, lane-dependent speed limits and lane divider marking types. The TomTom HAD map also contains a RoadDNA a localization layer providing road side depth 2D images to allow precise localization on the HAD map (see Section 5.1).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

To initiate the intended investigation on the use of HAD maps for the MAVEN automated driving scenarios, a joint workshop with all the involved partners was held. The objective of this workshop was mainly to agree on the investigation procedure. First of all it was needed to clarify the meaning of „HAD map precision“: Does it mean accuracy of the map representations compared to actual road layouts, or completeness of the data set provided looking at the needs of AD Software implementations? The answer in this case is that both meanings apply, as both are necessary to support the quality of automated driving implementations. The following Figure 7 highlights a mismatch between the HAD map's lane marking points and the actual lane markings which would oblige the AD trajectory planning and vehicle control to implement a „difficult“ sharper curve than it would be actually required to manual driving.

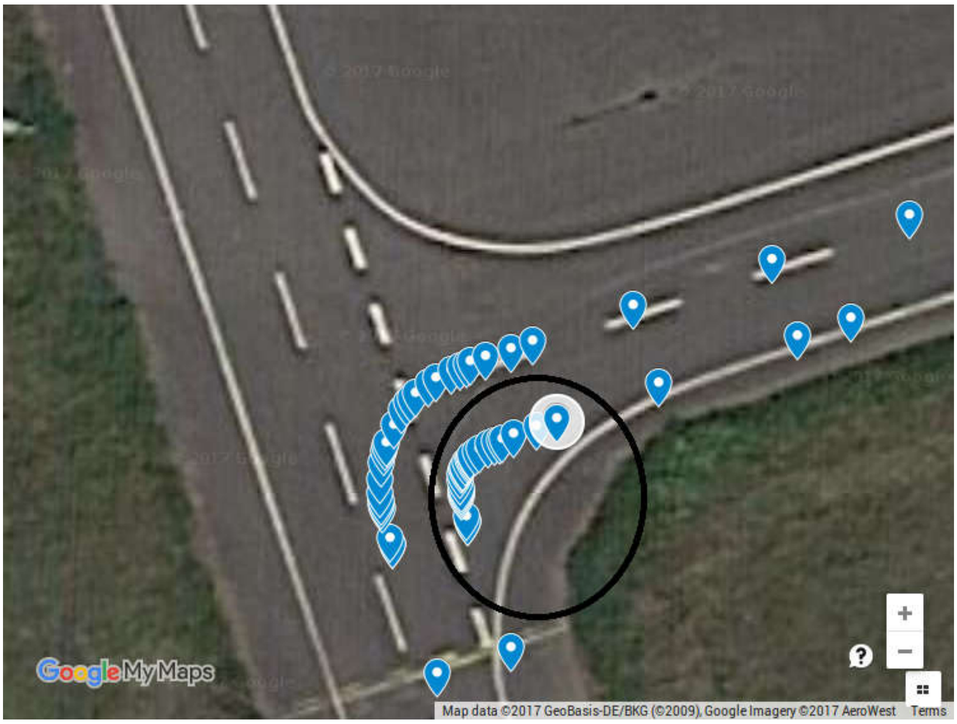

Figure 7: Mismatch between HAD maps information and actual road layout (visualized on GoogleMaps)

The second point in the workshop was to clarify the most suitable evaluation scheme to be used. Here an agreement was reached that evaluation of HAD maps can be done based on their capability to support the calculation of trajectory with satisfying quality, especially at complex scenarios like intersections.

On this basis the final HAD map requirements were identified and formulated. These requirements are a mix of generic HAD map requirements as extracted from a SoA analysis of related contributions from standardization, harmonization and industrial initiatives, as well as from requirements specific for the MAVEN automated driving use cases. It was in fact found that the current version of the HAD map was missing supporting information for the MAVEN vehicles to optimally plan trajectories at intersections. In the following these two sets of requirements are described.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

2.3.1 Generic requirements for HAD maps

Generic requirements for the HAD maps can be extracted from many sources, international standards, research projects and consortia, as they are often source of industry standards. In Europe, MAVEN has focused on SDOs like ETSI and industrial consortia like C2C-CC. Internationally, SDOs like ISO, SAE, consortia like 3GPP, OGC, OADF, NDS and ADASIS have been considered. The requirements were analysed, within the researched documents, from 4 different perspectives:

- Positioning precision requirements from C-ITS applications in standardization
- Map requirements in standardization and harmonization activities
- Location referencing methods in standardization, and
- Information requirements from C-ITS services

Each of these requirement classes are described in the next subsections.

2.3.1.1 Positioning precision for C-ITS applications from standardization

C-ITS applications for autonomous driving require high positioning accuracy. Positioning accuracy is defined as an ellipsoid of given dimensions, in which, with certain confidence, lies the actual position that is considered at the ego-vehicle and transmitted to other C-ITS stations. Based on the application these requirements may differ, see next list. It is important to stress out that in some cases the requirements refer to warning applications that anyhow are evolved to include automated vehicle reactions.

- Location precision for Cooperative Adaptive Cruise Control (C-ACC), Vulnerable Road Users (VRU) [11][12]
  - accuracy of the measured position with the 97-99,99 % confidence level.
  - location requirement: <0.5 - <0.1 meter depending on the automation level.
- Location precision for Intersection Collision Risk Warning (ICRW) [13]:
  - accuracy of the measured position with the 95 % confidence level.
  - for the triggering of a driver warning, the confidence level of the trajectories between two equipped vehicles shall be higher than 99 %.
  - location requirement: < 1 meter depending on the automation level.
  - Vehicle ITS Station shall be able to position itself in the lane it is moving in and signal its lane positioning to all other neighbour vehicles
- Location precision for needs of autonomous vehicles (white paper on C-ITS, "5G Automotive Vision" [14]. Position accuracy KPIs according to the use cases are defined:
  - Automated Overtake manoeuvres: 30 cm
  - Cooperative Collision Avoidance: 30 cm
  - High Density Platooning: 30 cm
  - Vulnerable Road User Discovery: 10 cm

This higher positioning requirement poses new requirements on the underlying map, its precision and its features.

2.3.1.2 Detailed road maps information from standardization and harmonization activities

From the positioning accuracy requirements, it is clear that lane level localization of a vehicle together with centimetre precision of relative location of its surroundings is needed. For maps, this

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

means that it has to be more detailed and that the so far used centreline for a road network representation, sufficient for navigation, will not be enough for cooperative automated driving applications. The following figure summarizes the landscape of map standardization. HAD maps requirements can be derived by the different standardization activities (some of them still ongoing) as described in the following.

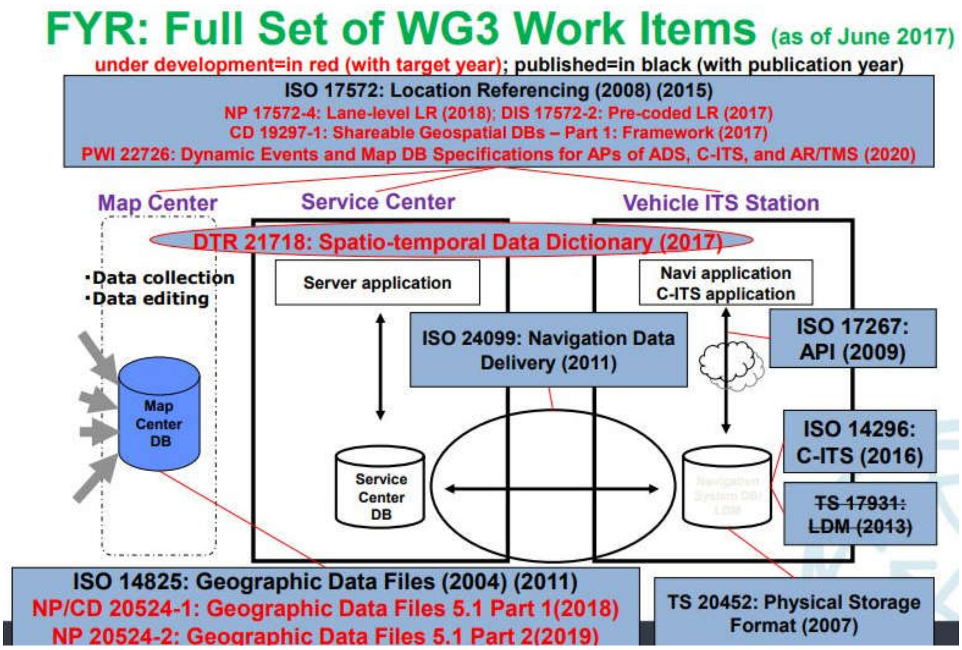

Figure 8: ISO TC204 WG 3 Geographic databases standardization [ISO 14825 GDF 5.1]

For setting the requirements in terms of needed information for lane location and within road area location, the new version 5.1 of the standard ISO 14825 Geographic Data Files [15] is being drafted (see Figure 8). This standard specifies map features, attributes, and relationship for Automated Driving Systems (ADS), C-ITS, and Multi-modal Navigation. The Geographic Data Files (GDF) itself defines the base map data set describing the road network and its characteristics. Many forms of location referencing are utilised, but this is substantively underpinned by the common concepts related to locating by coordinates. The GDF standard is currently being revised and extended. A part of this process of extension is defining concepts that enable the definition of traffic lanes within the GDF model, using concept broadly referred to as the 'Belt Concept'. Together with this standard, other standards related with this topic emerge: ISO 21718: Spatio-temporal Data Dictionary [16] that aims to assemble data dictionary covering ADS and C-ITS and ISO 17572-4: Lane-level Location Referencing [17] for developing new Location Referencing (LR) methodology enabling “Which lane?” referencing for C-ITS and “Where in lane?” referencing for ADS.

The ISO 14296: Extension of map database specifications for applications of cooperative ITS provides the map-related functional requirements, data model (logical data model/logical data organization), and data elements to extend the existing specifications for map databases in order to provide greater support for C-ITS applications that may use Local Dynamic Map [18]. The concept of Local Dynamic Map is specified in the standard ETSI EN 302 895: Local Dynamic Map (LDM) [19]. The LDM must be seen as an ITS dynamic information data base and not as a Navigation Map, although Navigation Map Elements can be part of the LDM. The LDM stores only

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors’ view and the European Commission is not responsible for any use that may be made of the information it contains.

that information that is relevant for applications and that allows dynamic location and time-depending decisions.
Besides the standardization activities running at different SDOs, other harmonization initiatives can be taken into account for deriving HAD map requirements in terms of detailed information to be included. In this context, the OGC Land and Infrastructure Conceptual Model Standard (LandInfra) [20] presents implementation-independent concepts supporting land and civil engineering infrastructure facilities. Conceptual model subject areas include facilities, projects, alignment, road, rail, survey, land features, land division, and wet infrastructure. It is based on a subset of LandXML. Another very important example in this direction is provided by OpenDrive® [21]. The OpenDRIVE® format provides a common base for describing track-based road networks using Extensible Markup Language (XML) syntax. The data stored in an OpenDRIVE® file describes – in an analytical way – the geometry of roads as well as features along the roads that influence the logics (e.g. lanes, signs, signals). The format is organized in nodes which can be extended with user-defined data. By this, a high degree of specialization for individual applications is feasible while maintaining the commonality required for the exchange of data between different (driving simulation) applications. Similarly, RoadXML [22] is an open file format for the logical description of road networks. The ambitions of the RoadXML are to take part in the standardization of road network format in order to enhance the interoperability between the simulators. To improve the content of road networks format to fulfil the objectives of future transport and travel with more respect to sustainable development and to build more realistic and efficient civil or military training applications.
At industrial level, The Navigation Data Standard (NDS) [23] is a standardized format for automotive-grade navigation databases, jointly developed by automobile manufacturers and suppliers. Members are automotive OEMs, map data providers, and navigation device/application providers. NDS aims to develop a standardized binary database format that allows the exchange of navigation data between different systems. NDS separates navigation software from navigation data, thus enhancing flexibility for creating various navigation products for end users. In addition to this interoperability, NDS databases support incremental updates, protection against illegal use, and compactness. Lately, the NDS association is working on standardized formats for inter-vehicle sharing of HAD map data suitable as a reference for automated driving applications. This includes detailed road layouts (lane topology, lane links, lane markings and marking rules), traffic rules, and environmental contextual awareness data (e.g. objects that can be used for positioning referencing).

2.3.1.3 Location referencing methods from standardization

To relay information about location to another road user messages with different location description methods are used.

- Geographic location referencing (GLR) defined in ISO 21219-21 (TPEG-GLR) is a special type of location referencing by coordinates of points, lines and polygons [24].
- Pre-coded location referencing as defined in ISO 14819-3 (ALERT-C) and ISO 17572-2 uses geographical feature attributes as a pre shared knowledge between information producer and consumer [25].
- Dynamic location referencing as defined in ISO 17572-3 (AGORA-C) [26], ISO 21219-22 (OpenLR from TomTom) [27] or ISO 21219-11 (TPEG-ULR) uses static map features to create on the fly description of a location. A combination of simplified network geometry and a set of specific road characteristics is exchanged.

The location description stated above is used within the framework of traffic messages. Two main message formats are used: DATEX II and TPEG 2.0, both allowing wide selection of the location

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

referencing method. For direct vehicle-to-vehicle message exchange including location, other message standards are used:

- SAE J2374_199907 [28] and SAE J2266_2004106 [29] Location Referencing Message Specification provides a practical approach to standardization for location referencing within a mixed data set environment, i.e., where more than one kind of spatial data set exists, and where spatial references between these data sets must be made.
- SAE J1746_1999126 [30] ISP-Vehicle Location Referencing is intended to be used for the communication of spatial data references between central sites and mobile vehicles on roads. References can be communicated from central site to vehicles or from vehicles to central sites.

2.3.1.4 Detailed information requirements from C-ITS services

There are several positioning and location-based requirements that can be extracted from the V2X communication services used in the MAVEN use cases. The MAVEN communication services specify the V2X messages (CAM, MAP, SPaT, LAM, CPM) to be exchanged through C-ITS interfaces, between vehicles and or infrastructure. All of these interfaces are described together with precise message definitions in the deliverable D5.1 [5].
The key static / dynamic information transmitted in these messages relates to positional arguments of HAD maps:

- Planned Route of intersections to cross
- Planned route at intersection (ingress-lane, signal group for planned manoeuvre, …)
- Planned path (trajectory)
- Object on the road (Id, position (in delta or absolute values), speed, heading, acceleration, length, width, objectType (pedestrian, vehicle, bike, etc.))
- Intersection topology: List of lanes (ingressing and egressing lanes)
- Laneposition (actual lane position retrieved from e.g. HD map and/or GPS position)

The Local Dynamic Map (LDM) implemented at both MAVEN vehicles and infrastructure is the central data collection point. All MAVEN use case- relevant dynamic data is stored here with logical geographic references to the underlying HAD map. The information included in the MAVEN V2X messages however does not directly impose requirements on the HD map precision. It is responsibility of the V2X message providers to make sure that topological descriptions included in the messages are precisely respecting the actual road layouts and that the transmitted positions comply with the confidence values described in Section 2.3.1.1. The only requirement posed by V2X communication services to the HAD map is that some road topology identifiers adopted in the messages (lane, intersection IDs, etc.) are accordingly reflected in the HAD map representations. This will ease the implementation of AD algorithms when matching the information received via V2X with the corresponding information of the HAD maps.

2.3.2 MAVEN requirements for HAD map extensions

While covering most of the requirements highlighted in the previous subsections, it was found out that the TomTom HAD map did not provide important information for allowing MAVEN cooperative automated driving manoeuvring at intersections. To solve this limitation, the MAVEN partners came up with the definition of intersection „corridors“ as those virtual lane markings connecting inputs and output lanes where the AD SW is allowed to derive a possible trajectory. These corridors need to be included in the HAD map road network representation format and have to include also virtual stop lines where cars have to stop to give way to incoming traffic in case of

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

conflicting manoeuvers and have to additionally include same topological information as transmitted in V2X messages. An example of how the corridors would look like in the specific case of the Braunschweig Tostmannplatz test site is depicted in the following Figure 9.

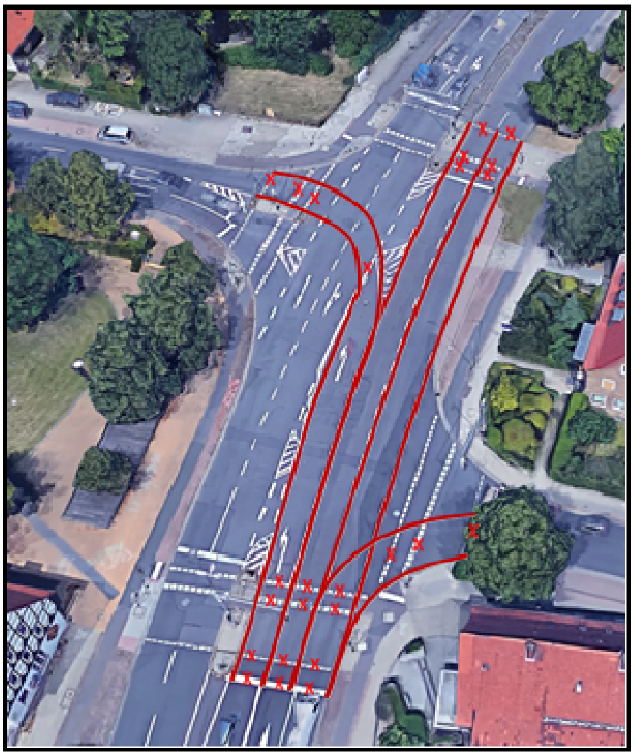

Figure 9: Ideal MAVEN intersection corridor representation for the Braunschweig Tostmannplatz test site (visualized on GoogleMaps)

Technically speaking, a corridor is a pair of "virtual boundary lines" that connect the boundary lane markings of inbound lanes to boundary lane markings of outbound lanes. They are “virtual” because they might not reflect actual lane markings. In fact, inside intersection areas, these lane markings are generally not present. The area inside the corridor is the area where driving is allowed for making a given straight or turning manoeuvre, which means that the vehicle not necessarily drives on in its centre as long as it is within the corridor boundary lines. The corridor should match the reality to make sure that they do not include obstacles such as "intersection islands", etc. (See Figure 9).
Formally, the MAVEN desired attributes for corridors are:

- **Start/end of corridor:** start can correspond to an actual stop line marked on the road surface or it can be a "virtual stop line" indicating where the vehicle should stop not to be an obstacle for traffic coming from other inbound lanes
- **Corridor boundary lines:** to be represented as polynomials or set of consecutive points
- **Corridor centre line**: to be represented as polynomials or set of consecutive points
- **IDs of side corridors**: in case two corridors are parallel the ID of the adjacent corridor is needed

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors’ view and the European Commission is not responsible for any use that may be made of the information it contains.

In addition to corridors, the MAVEN HAD map extended format has to include the following information:

- **Info for matching with C-ITS topology representations:** Another requirement for intersection scenarios is information for matching the IDs of the HAD map lane drivable by automated vehicles with the IDs included in the C-ITS intersection topology representations, in particular those included in the C-ITS message MAP standardized at SAE [31]. A MAP message includes for each intersection inbound and outbound lane an unambiguous laneID. These laneIDs shall be included as attributes in each of the corresponding lanes of the HAD map representation.
- **Boundary lines of pedestrian/bicycle crossing lanes:** to be represented as polynomials or set of consecutive points

The above needed extensions shall be included in the HAD map databases provided by TomTom for real road evaluations on the MAVEN test sites. For the Hyundai vehicle, the TomTom HAD maps are directly used in the AD SW framework running in the vehicle [32][33]. For the DLR vehicles, the OpenDRIVE® [21] HAD map format is used so a conversion of the TomTom databases is needed. An automatic 1:1 conversion of the TomTom input data is not possible yet due to missing conversion toolchains. The chosen approach was to follow the Road2Simulation guidelines (R2S) [34] and to use the proposed intermediate format which allows automatic conversion at least from Road2Simulation into OpenDRIVE®[21]. The transformation of TomTom data into R2S yet cannot be done automatically, too, but can be performed manually much easier because both share a common OGC Simple Feature [35] representation. In order for this task to be achieved the required minimal R2S elements have to be derivable from the TomTom data which are: reference lines, outer lane borders and road marks. For standard road segments this requirement is fulfilled but in intersection areas the above mentioned corridor information is needed.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

3 ADAS functions development

This section describes the ADAS functions developed individually by the involved MAVEN partners, referring to the scheme reported in Section 2.1. Each subsection indicates the functional behaviour of the developed scheme followed by a description of the evaluation method adopted and finally the test results.

3.1 Hyundai developments

In MAVEN, HMETC has developed functionalities for safe consideration of VRUs and obstacles in its MAVEN AD SW architecture, with application for automated detection and reaction when turning at road intersections. In the following, these functionalities will be presented following the classification scheme introduced in Section 2.1.
The described functionalities are based on the Hyundai AD vehicle sensor setup as described in [32] and depicted in Figure 10. This setup is composed by the following sensors:

On-board sensors:

- 1x Ibeo front + 1x Ibeo rear LiDAR,
- 1X Mobileye front Camera (CAM),
- 4 x Aptiv SRR4 corner radars,
- Aptiv MRR3 front radar

Cooperative Sensors:

- Cohda MK5 OBU (V2X communication module)

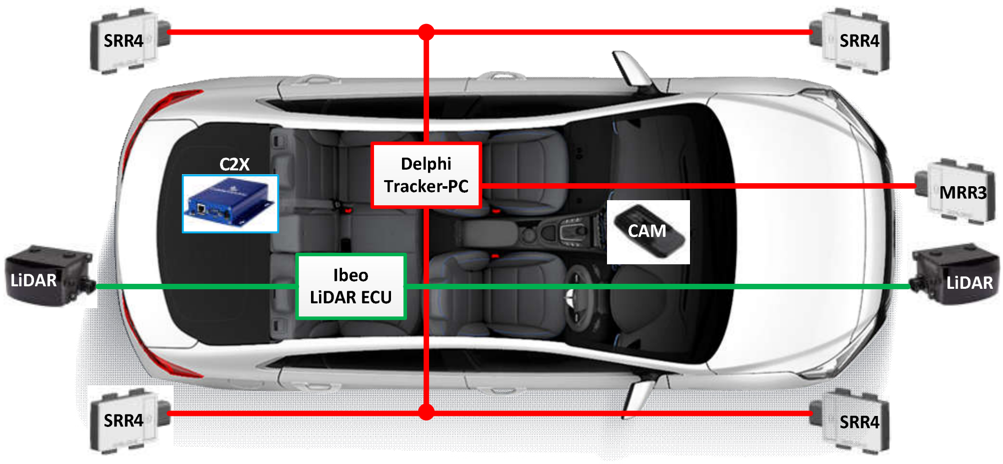

Figure 10: Hyundai vehicle sensor setup for functionalities evaluation

It is important to stress out that these sensors are not experimental samples but are either already installed in series vehicles, or are close to be. Moreover, the overall sensor setup is designed to be affordable without drastically compromising the capability to sense the surrounding environment and hence support automated driving functionalities. In this context, especially the reduced amount

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

of LiDARs used compared to other AD vehicles prototypes (generally supporting 3 LiDARs in the front or roof mounted 360° scanning LiDAR solutions) permits having an experimental testing platform for understanding the limits of an affordable sensor setup and how these limitations can be overcome by collective perception solutions.
For easing the understanding of the following subsections, a basic overview of the Hyundai automated driving software framework implementation is also reported in Figure 11. As it can be seen, the sensor fusion module collects inputs from the individual sensors (including the V2X communication module) and provides a consolidated representation of the environment to the Guidance, Navigation and Control module (GNC). The guidance and control module is devoted to compute the planned trajectory and vehicle control. In this block, the Decision Making Module (DMM) can support a threat assessment based on the vehicle route, and the obstacles detected in the drivable region. As such, it is used to drive deceleration/stopping decisions and hence has an impact on the trajectory and control computation.

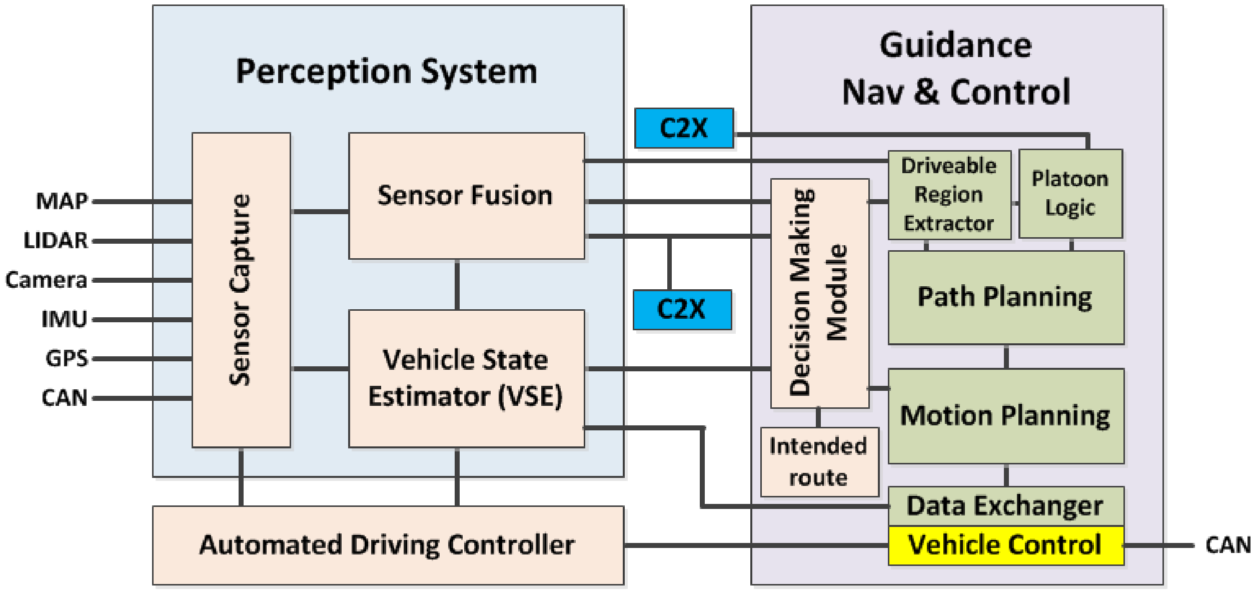

Figure 11: Hyundai AD SW Framework, basic overview

3.1.1 VRU/obstacle consideration at intersection based on on-board sensors

3.1.1.1 Functional behaviour

As mentioned before, the objective of the HMETC developments in the investigation of functionalities for protection of VRUs and AD vehicle drivers is to understand the limitations of affordable sensor setups and how these limitations can be compensated by collective perception approaches. In order for this investigation to be as reliable as possible, and for contextualization within the MAVEN scope, critical evaluation scenarios such as intersections are considered. At road intersections, the detection and reaction capabilities of AD vehicles get particularly stressed by several factors. First, the common presence of large sized obstacles like buildings can partially or totally obstruct the line of sight of important sensors like cameras, radars or LiDARs pointing to the front and hence hide possible objects on the planned route (see Figure 12, where the red

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

vehicle that plans to turn right has the crossing pedestrian hidden by the building). Second, in case of turning manoeuvres, the on-board sensors need some time before being aligned to point the direction of the object. Additional time is needed to track the obstacle not to confuse it with a false positive (e.g. in Figure 12, the red vehicle might not have enough time to detect and track the crossing pedestrian while turning right, and consequently might hit him). Finally, intersection are commonly crowded, which increase the possibility of false detections when obstacles like VRUs are right at the border between the drivable region and the area dedicated to other road users.

Figure 12: Typical intersection scenario with obstructed VRU

In this context, the HMETC AD SW implementation incorporates in the Guidance, Navigation and Control (GNC) module (Figure 11) the logic to perform lane change and stop & go behaviours to prevent collisions with obstacles in the direction of travel. For this purpose, the Decision Making module takes as inputs the list of detected and tracked objects as well as the list of lanes information from the Sensor Fusion module. This information is crossed with the ego vehicle state (heading, speed, position, etc.) from the VSE and with the intended route as received from the global route planner module. Moreover, the DMM can receive triggers to adapt the vehicle speed or change the lane based on C2X receptions from the infrastructure and has to also consider the presence of traffic signs, speed limits, etc. from HAD maps. Based on all these inputs, the DMM generates two outputs: a so called “feasible manoeuvre” and an “object threat list”. A feasible manoeuvre such as lane change, go straight, stop, keep distance and possible associated speed and or distance values are computed based on the priority of the various inputs like intended route, object list, C2X speed and lane change advice, traffic signs from HAD map data, etc. The object threat list is a set of objects whose position and dynamics currently constitute a threat (e.g. risk of collision) when compared with position and dynamics of the ego vehicle. Feasible manoeuvre and object threat list are given as inputs to the path planner module. Based on them, the path planner module continuously computes a reference goal point and, by exploring all the possible paths to reach it, selects the most suitable one. As mentioned before, to prevent a collision the reference goal point can imply stopping at a given distance from an obstacle or performing a lane change.

In the context of the MAVEN, the above mentioned functionalities apply to straight streets, but most importantly also to intersection scenarios thanks to making use of HAD maps supporting the requirements of Section 2.3, and implemented by the format described in Section 4.1.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors’ view and the European Commission is not responsible for any use that may be made of the information it contains.

These functionalities are intended to be applied and tested in typical intersection scenario as depicted in Figure 13. The ego vehicle is turning right and is going to collide with a crossing pedestrian. If the pedestrian is correctly detected and tracked by the sensor fusion module, the DMM will decide to trigger a lane change at a given distance $d_{lanechange}$ depending on the current ego-vehicle speed and if allowed by the road topology (i.e. minimum two lanes available for the direction of travel). Otherwise, the DMM will decide to stop d_{stop} meters before the VRU. If the pedestrian is detected and tracked after this distance (as it is likely to happen in the depicted intersection scenario with right turning), then a hard brake is triggered as soon as the VRU is assessed to be a threat.

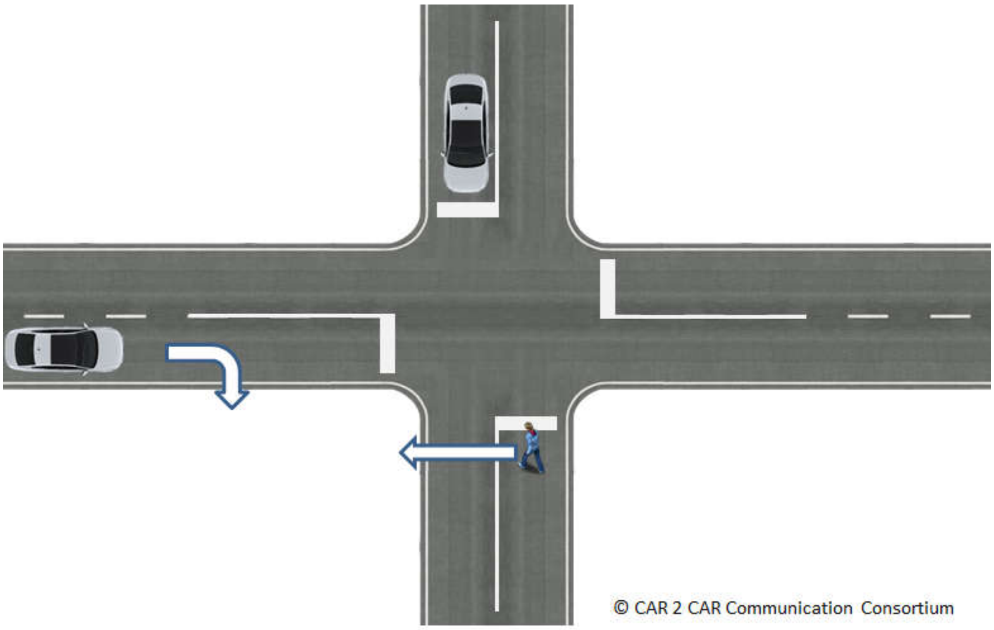

Figure 13: Intersection scenario for evaluation of VRU/obstacle consideration based on on-board sensors

3.1.1.2 Evaluation method

The above mentioned functionality has been tested on the Griesheim test track [36] using the intersection depicted in Figure 14. A pedestrian dummy is used to cross the intersection at a configurable distance d_{int} from the intersection centre. The ego vehicle is started to drive automated from a given fix point along one of the intersection approaches, which results in a fix distance to cover to the point of collision with the VRU. The pedestrian dummy is moved in such a way to be on the lane driven by the ego vehicle right after turning right. As only one lane is allowed to be driven in the direction of travel of the ego vehicle, a lane change cannot be triggered to avoid a collision with the VRU. On the contrary, the ego vehicle AD logic is programmed to stop at a distance d_{stop}=7m from the obstacle, or to brake as soon as the obstacle is detected, tracked and assessed as a threat.
The investigated functionality is evaluated for two different values of the d_{int}, respectively 16m and 28m.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

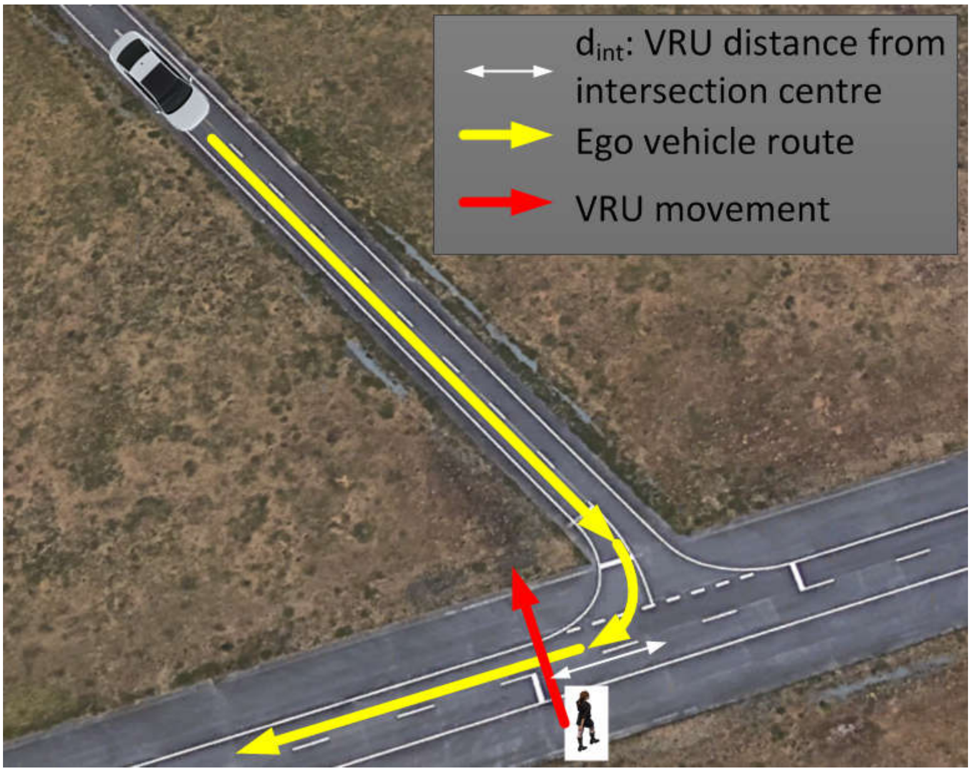

Figure 14: Evaluation setup for VRU/obstacle consideration based on on-board sensors (visualized on GoogleMaps)

3.1.1.3 Evaluation results

Figure 15 depicts a picture of the performed tests, where the ego vehicle and the pedestrian dummy are visible right before a possible collision.

Figure 15: Test execution of VRU/obstacle consideration at based on on-board sensors

The results of the evaluations are shown in the next two figures, representing the motion profile of the ego vehicle in terms of speed as a function as the distance covered. Both the speed computed by the motion planner and the actual speed applied by the vehicle controller are depicted.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

In Figure 16, the results of the test with the pedestrian crossing at d_{int}=28m are shown. As it can be seen, the vehicle starts to speed up to reach the goal speed of 50kmph and then it starts to slow down to reach the stop line at a relatively low speed allowing a comfortable turn to the right (10Kmph after covering 150m). When turning, the ego vehicle starts to speed up again in order to reach the goal speed over the new straight stretch. As the VRU is not directly placed right after the curve (it is actually shifted 12m to the left compared to the position in Figure 14), the ego vehicle has enough time to detect, track the VRU, assess it as a threat and trigger a stop right in front of it (~1,5m over various experiments). This behaviour is visible in the motion profile by looking at the actual speed falling rapidly from 17 to 0kmph.

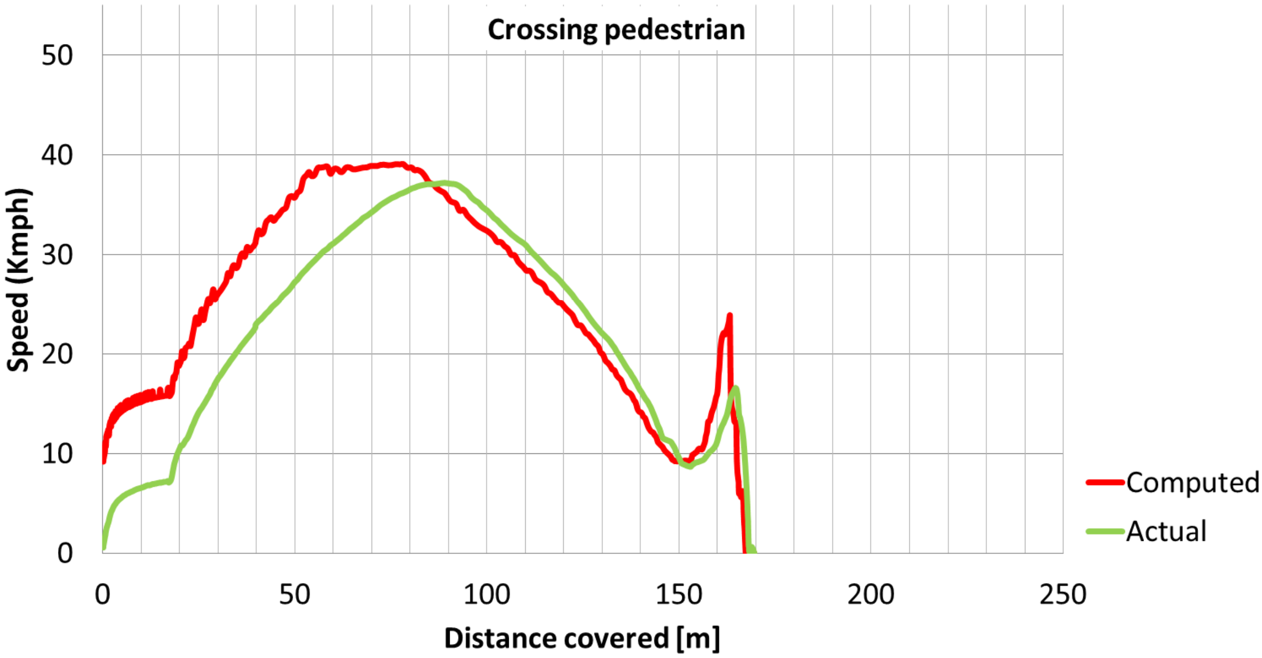

Figure 16: ego-vehicle's motion profile when VRU crosses at 28m from the intersection centre

In order to understand if the same performance applies when the VRU is closer to the intersection centre right after the vehicle turns, the dummy is moved to a distance d_{int}=16m from the intersection centre (as shown in Figure 14). The results of the corresponding tests are depicted in the next Figure 17. As it can be seen, similarly to the previous experiment, the ego vehicle speeds up and then slows down before the curve. After reaching the stop line and starting to turn, the speed ramps up again. In this case, the AD logic has not enough time correctly detect the VRU as a threat. This is due to the fact that the vehicle sensors are not all pointing to the position of the obstacle till right before the collision. Moreover, detections from individual sensors (in particular the corner radars) are hampered by the small dimensions of the VRU. The sensor fusion cannot obtain a robust and stable detection to be distinguished from many other false positives. As a result of the lack of a timely threat assessment, the ego vehicle is going to collide with the dummy, and has to be manually braked (visible in the figure as an instantaneous speed fall to 0).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

Figure 17: ego-vehicle's motion profile when VRU crosses at 16m from the intersection centre

It is then evident that in order to ensure higher levels of safety, suitable countermeasures are needed. In the next subsection it is explained how the introduction of the collective perception approach can overcome the limitations of functionalities that rely on on-board sensors only without requiring expensive extensions of the sensor setup.

3.1.2 VRU/obstacle consideration at intersection based on CPM receptions from vehicles

3.1.2.1 Functional behaviour

As explained in the MAVEN deliverable D5.1 [5], future cooperative automated driving will benefit from the presence of other C-ITS actors (vehicle or road infrastructure) continuously sharing information about locally detected objects via V2X communications. This information will be particularly valuable in situations and scenarios like those referred in the previous subsections. Objects or VRUs that cannot be detected in time by the ego vehicle's on-board sensors can be "advertised" by other C-ITS actors to whom they are currently visible. This advertisement is done by continuously transmitting Collective Perception Messages (CPMs) containing abstract descriptions of those objects indicating their position and dynamics [5]. By leveraging this approach, the Hyundai AD logic has been extended with a functionality to take CPM information into account when operating threat assessments, manoeuvring decisions, and path and motion planning. This functionality has been applied to the intersection scenario depicted in the next Figure 18.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

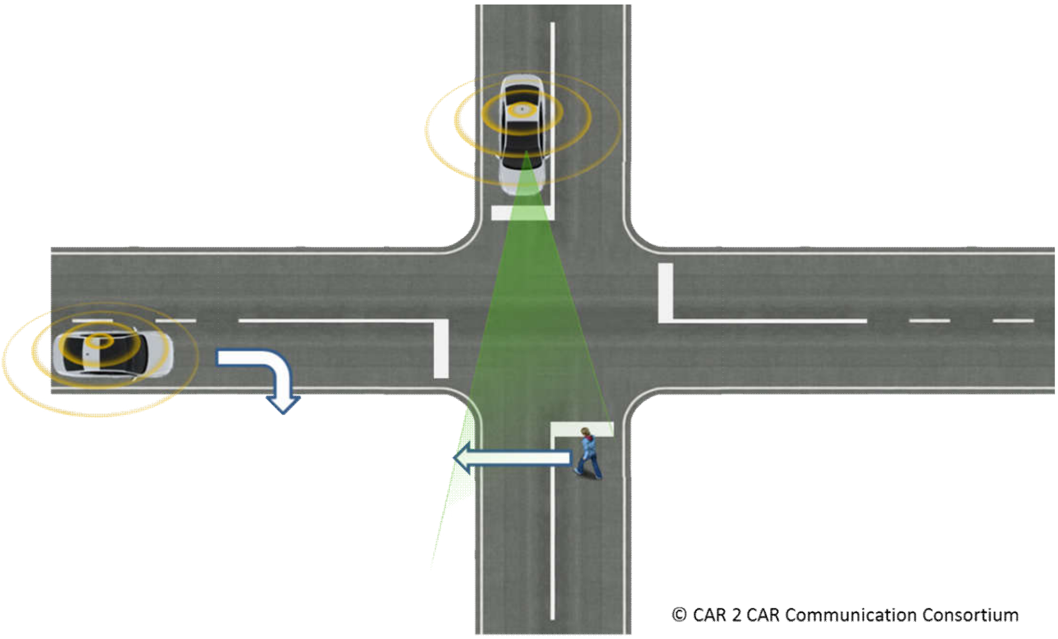

Figure 18: intersection scenario for evaluation of VRU/obstacle consideration based on CPM receptions from vehicles

The ego vehicle will consider CPM receptions from other vehicles. In Figure 18, these receptions are result of CPM transmissions by another vehicle that can currently detect the crossing VRU thanks to his favourable alignment with the vehicle's sensors.

In general, the CPM information is provided to the AD logic's sensor fusion, which in turn delivers additional inputs to the DMM to perform its threat assessment and manoeuvre feasibility choices. The advantage here is that the DMM is informed about the presence of objects along its route much before they enter in the field of view of the on-board sensors, hence permitting more conservative and context-aware decisions and plans. In particular, the DMM starts considering CPM information when the CPM objects are 100m away along the planned route, and accordingly can decide to slow down/change lane earlier according to the relative speed between the ego-vehicle and the obstacle. In Figure 18, the ego vehicle is turning right and is going to collide with a crossing pedestrian. If the pedestrian is correctly detected and tracked by the sensor fusion module (here extended to also consider CPM receptions), the DMM will decide to trigger a lane change at a given distance $d_{lanechange}$ depending on the current ego-vehicle speed and if allowed by the road topology (i.e. minimum two lanes available for the direction of travel). Otherwise, the DMM will decide to slow down and eventually stop d_{stop} meters before the VRU. If the pedestrian is detected and tracked after this distance, then a hard brake is triggered as soon as the VRU is assessed to be a threat.

3.1.2.2 Evaluation method

This functionality has also been tested on the Griesheim test track [36], this time using the scenario depicted in Figure 19. A pedestrian dummy is used to cross the intersection at the distance d_{int}=16m from the intersection centre. This distance was challenging for the functionality described in Section 3.1.1. The ego vehicle is started to drive automated from a given fix point along one of the intersection approaches, which results in a fix distance to cover to the point of collision with the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

VRU. The pedestrian is moved in such a way to be on the lane driven by the ego vehicle right after turning right. As only one lane is allowed to be driven in the direction of the ego vehicle, a lane change cannot be triggered to avoid a collision with the VRU. On the contrary, the ego vehicle AD logic is programmed to stop at a distance d_{stop}=7m from the obstacle, or to brake as soon as the obstacle is detected, tracked and assessed as a threat.

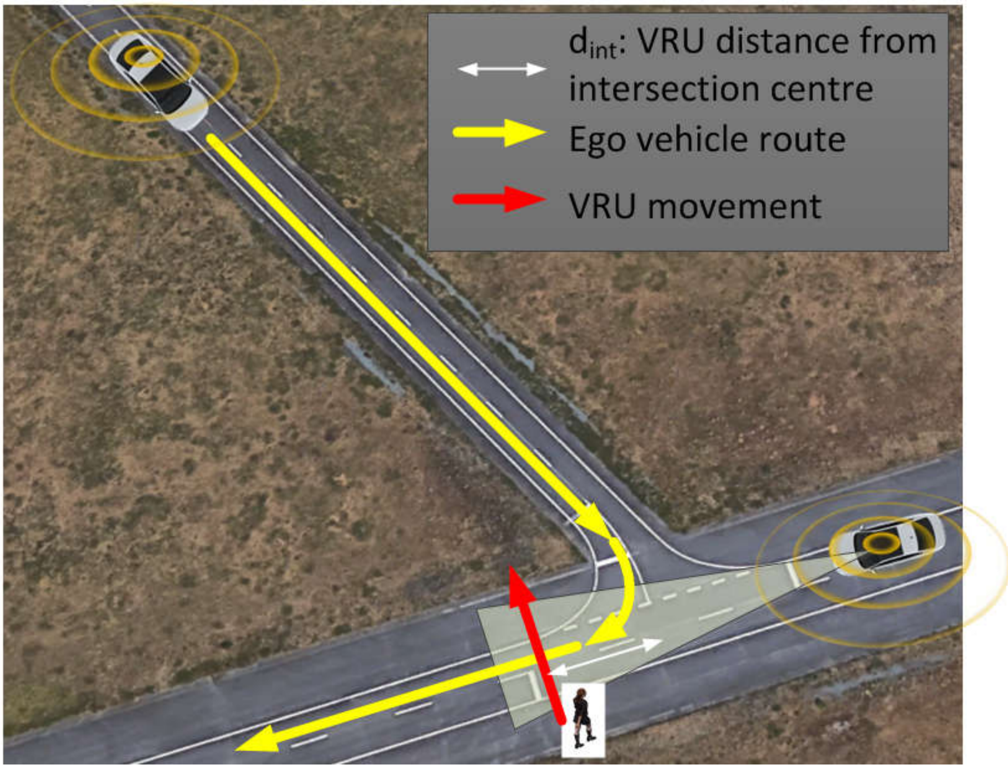

Figure 19: Evaluation setup for VRU/obstacle consideration based on CPM receptions from vehicles (visualized on GoogleMaps)

For the provision of the CPM information at the ego vehicle, a CPM reception emulation approach is used. This is due to the fact that HMETC only has one AD vehicle prototype able to detects objects and transmit/receive CPM messages, so only one vehicle can be used at the time. The emulation approach works as depicted in Figure 20. The AD vehicle is first used as CPM transmitting vehicle. It is placed in front of the moving dummy (right car in Figure 19) and records the results of the sensor fusion module as the VRU crosses the street (see also Figure 21). For CPM transmissions, the sensor fusion module considers inputs from front camera, front radar and front LiDAR and populates CPM messages with objects that are concurrently detected by these three sensors. In this way, the probability to transmit false detections in CPMs is strongly reduced, which in turn provides meaningful and useful information to the receivers. The sensor fusion outputs (fused object data in Figure 20) are converted into ROS bag files and recorded in the format as they would be transmitted within CPM messages. The ROS bag files are then “replayed” within the AD SW logic of the ego-vehicle (top car in Figure 19) when performing the test for collision avoidance with the crossing pedestrian. This replaying of the bag file is emulating the receptions of CPM messages from the transmitting vehicle (a virtual vehicle in this case). Of

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors’ view and the European Commission is not responsible for any use that may be made of the information it contains.

course, in this test the pedestrian dummy is moved in a synchronized way to be in the same positions as “played” with the bag file.

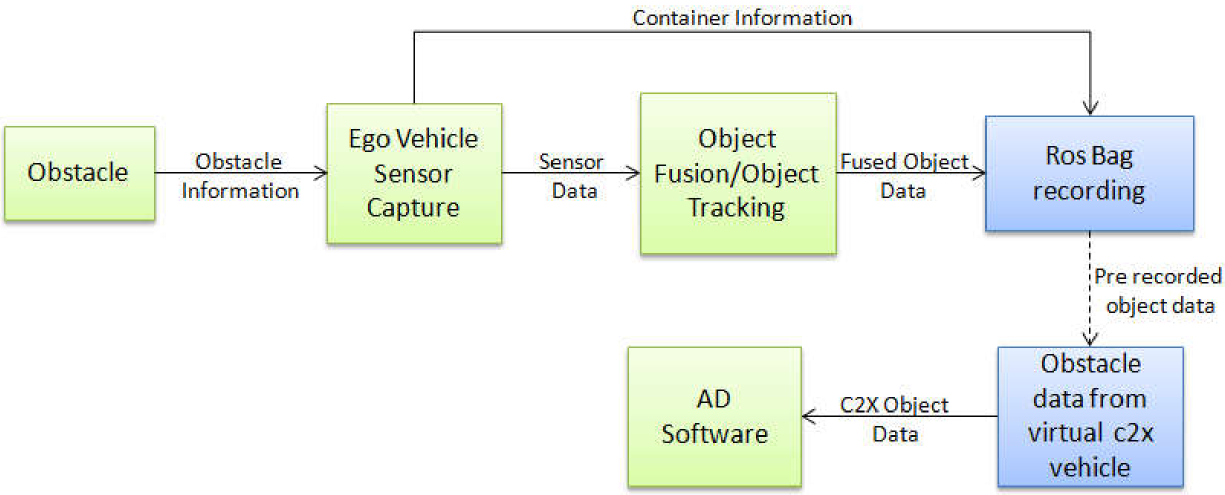

Figure 20: CPM emulation approach

Also, it is important to stress out that the ROS bag files’ replaying at the ego vehicle’s AD SW is done by activating a UDP socket transmission from a virtual V2X vehicle (lower blocks in Figure 20). For this UDP communication, exactly the same format is adopted as defined for the UDP communication between the AD SW and the V2X communication module. This UDP communication adopts specific structures transmitted over a dedicated IF6_V2X2CP interface as described in Section 3.1 of Deliverable 5.1 [5]. This implies that replaying a bag file at the AD SW is exactly like receiving UDP frames from the V2X communication module when CPM messages are received from other vehicles.

Figure 21: Test preparation, recording of CPM information to be replayed by the ego vehicle

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors’ view and the European Commission is not responsible for any use that may be made of the information it contains.

3.1.2.3 Evaluation results

As mentioned before, the advantage of using the CPM approach is that the DMM has information about objects not detectable by the ego sensors at earlier stages in order to timely react. The next Figure 22 depicts a screenshot of the visualization tool adopted to identify the objects currently considered by the DMM module for its threat assessment decisions. The white box on which the axes are centred is the ego vehicle. The yellow point represents the VRU dummy detected via CPM receptions. As it can be seen, the dummy is small-sized compared to the other objects detected via ego sensors (purple boxes). The other grey points are HAD map points. The dummy is hence detected to cross the road profile much before the ego vehicle starts turning.

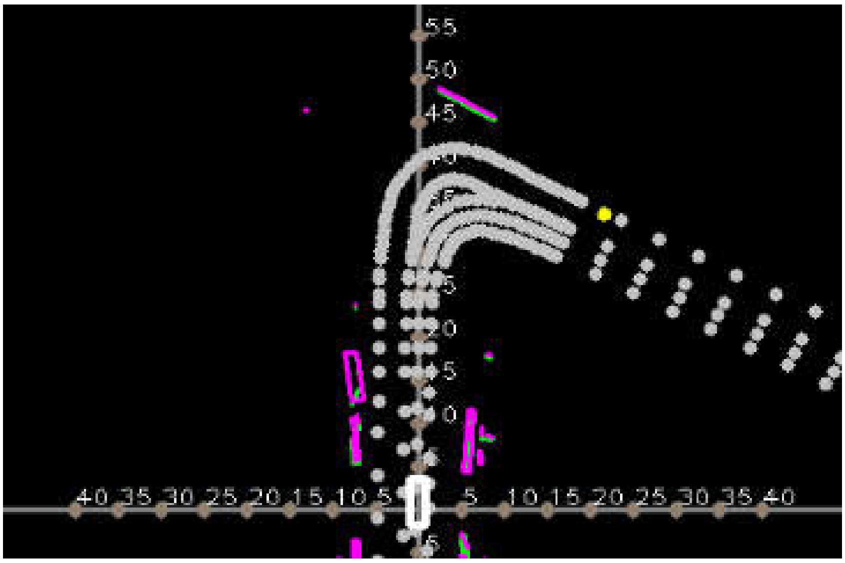

Figure 22: Test execution, CPM information in the visualization tool on the ego vehicle

The results of the evaluations are shown in the next two figures, representing the motion profile of the ego vehicle as described in the previous subsection.
Figure 23 shows the results of the test with the pedestrian crossing at d_{int}=16m and the ego vehicle turning when the dummy is currently on the lane along its route. As it can be seen, like in Figure 16 the ego vehicle slows down to reach the stop line at a relatively low speed allowing a comfortable turn to the right (10Kmph after covering 150m). Differently from what shown in Figure 16, when turning, the ego vehicle does not speed up. Instead, it further slows down as a result of taking the VRU presence into account in the DMM module. The ego vehicle then stops in front of the dummy and wait for it to move out of the driven lane (the speed goes to 0 approximately 163m after starting to drive). When the dummy is completely out of the lane, it is not considered as a threat any longer. As a consequence, the ego vehicle’s speeds ramps up to reach the goal speed of 50 Kmph on the straight stretch. The same results could be visualized with the speed profile as a function of the elapsed time. In this case, it would be seen that the speed stays null for a given time needed for the pedestrian to move out of the lane.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors’ view and the European Commission is not responsible for any use that may be made of the information it contains.

Figure 23: AD vehicle motion profile in case a collision with crossing pedestrian has been prevented via CPM information consideration

It is important to stress out that the DMM threat assessment should not be too conservative in performing threat assessment decisions. More specifically, the DMM should not unnecessary modify the normal motion profile (slowing down the vehicle) when no risk is detected, as this can negatively affect the AD vehicle drivers' user acceptance. To investigate this aspect, the next Figure 24 shows the results of the test with the pedestrian crossing at d_{int}=16m and the ego vehicle turning when the dummy is already out of the lane along the ego vehicle route. As it can be seen, differently from Figure 23, the ego vehicle does not decelerate and stop when turning. On the contrary, it speeds up to reach the goal speed over the straight stretch as the DMM knows that the pedestrian has already crossed and is finally out of the driven lane.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

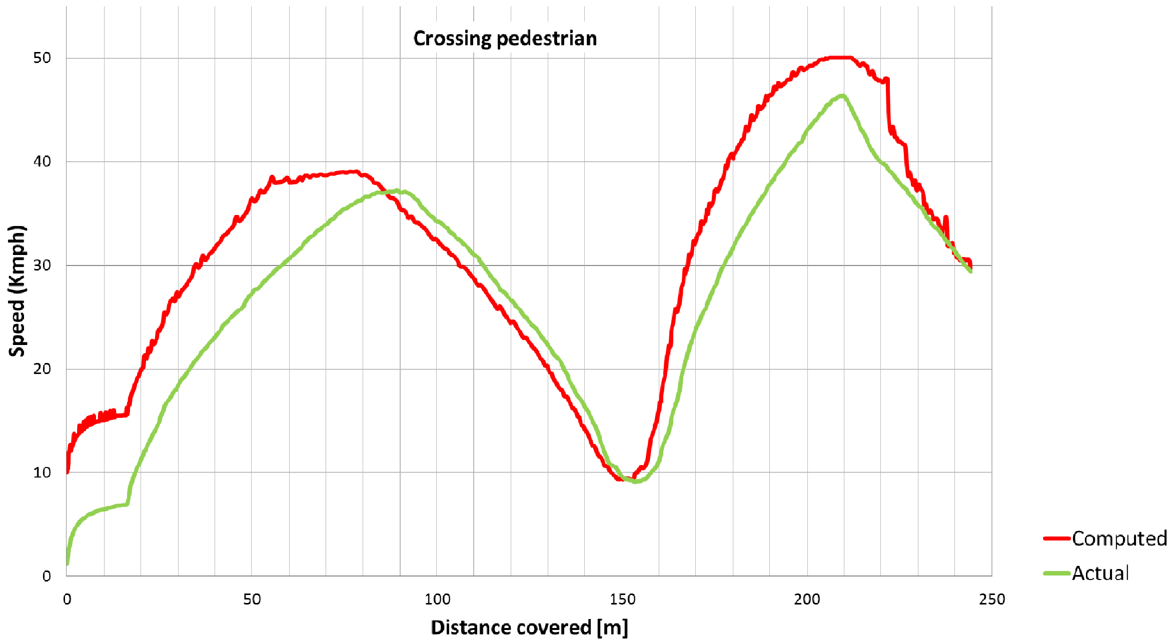

Figure 24: AD vehicle motion profile in case of no risk of collision with crossing pedestrian detected via CPM information consideration

3.2 DLR developments

The developments of DLR have been aligned to the developments of Hyundai. Figure 25 shows the sensor setup of the vehicle which has already been described in detail in D6.1 [32]. This setup has been used for all test drives during the project so far. The setup of the new vehicle ViewCar2, which is also part of the FASCar fleet, is equipped in a similar way.

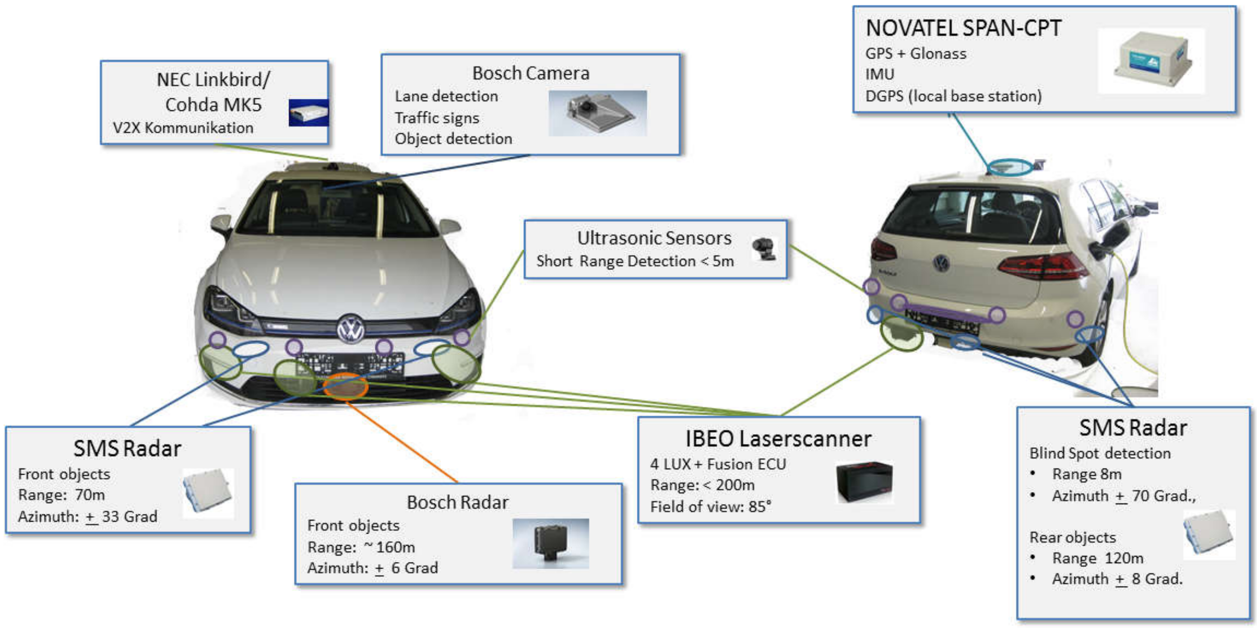

Figure 25: DLR FASCarE vehicle sensor setup

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

A brief overview of the software system used in both DLR vehicles is shown below. Please note that a more detailed perspective on the modules is shown in D3.1 which will be published later on in the project. Compared to the same figure of the Hyundai vehicle, there are only a few differences in terms of naming, and only a few different modules. To allow cooperative perception, the DLR vehicle is equipped with additional sensor interfaces which allow the input of CPMs and CAMs into the sensor data fusion. The data of both messages is used to enrich parameters of already tracked objects or to add obstacles, which are hidden or not recognized by local sensors yet. On the other hand, obstacles detected by the vehicle itself with local sensors can also be forwarded as CPMs. As not all vehicles are of interest, to the surroundings, the list of obstacles included in the CPMs can be filtered.
In addition to this, the sensor fusion also has an input for virtual vehicles. This feature is used for testing of complex or dangerous situations, esp. for achieving more test cases for vehicle automation.
All platooning behaviour is managed by the Platoon Logic module which is responsible for providing the necessary information for platooning to the local vehicle automation, to other platoon members and the surrounding vehicles and infrastructure.

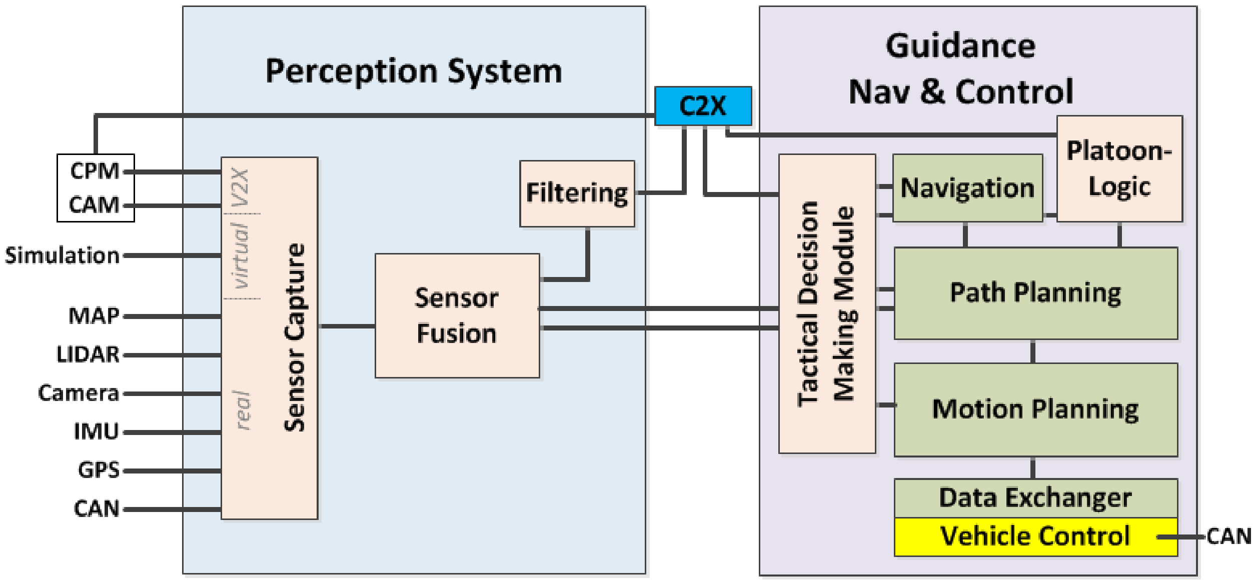

Figure 26: DLR AD SW Framework, basic overview

3.2.1 VRU/obstacle consideration at intersection based on CPM receptions from infrastructure

3.2.1.1 Functional behaviour

The following sensors are used (please refer to D6.1 [32] and D6.2 [36] for more details on the systems):

- Infrastructure Sensor 1 (commercial road surveillance system)
- Infrastructure Sensor 2 (Hemispheric Camera)
- Highly automated vehicle 1 (FASCarE)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

- Highly automated vehicle 2 (ViewCar2)

The **infrastructure** equipment of DLR includes a road side surveillance system build by a third party (commercial road surveillance system) and a self-tailored experimental system. The different systems cover different ranges of requirements. The commercial system is well tested, 24/7 approved and uses well established and mature detection algorithms. The self-tailored experimental system allows for using cutting edge deep learning technology for the detection of road users and for data fusion. It allows gaining experience with technology supposed to be commercially available in the future. However, this is for the sake of reliability and maturity. Both systems are used on the Tostmannplatz test site. This infrastructure of the future is supposed to be heterogeneous. Collective perception approaches need to cope with this situation.

The functions implemented for the **infrastructure** side are as follows (see also Figure 27):

- The system interfaces with the hemispheric Surveillance Camera. A Samsung PNM-9020 Camera with an OnVif interface is installed on the test site.
- The system creates rectified images for 4-8 virtual perspectives out of the hemispheric image.
- The system detects motorized vehicles and VRUs in the rectified image sequence. An image processing server with 14336 CUDA [37] cores for parallel computing is installed on the test site for this purpose.
- The system detects optical flow in the rectified images
- The system performs data fusion of the detections and the optical flow for road user tracking. A track stitching approach using the network flow algorithm is implemented for this task. Figure 28 shows examples for different tracking scenes.
- The system transforms the object hypotheses from the image plane to the ground plane.
- The system performs road user re-identification for stitching the trajectories from the different virtual perspectives.
- The system generates Collective Perception Messages and transmits them over V2X (Linkbird Hardware)
- The system detects VRUs and obstacles.
- The system predicts VRU trajectories and trajectories of all other road users and detects potential conflicts where the trajectories of motorized vehicles and VRUs intersect.
- In case of a conflict, a DENM or SOM is created, similar to [43]. In contrast to the generally sent CPM, which also covers most of the SOM, i.e. the local dynamic map of the area, this message is indicating the warning part.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

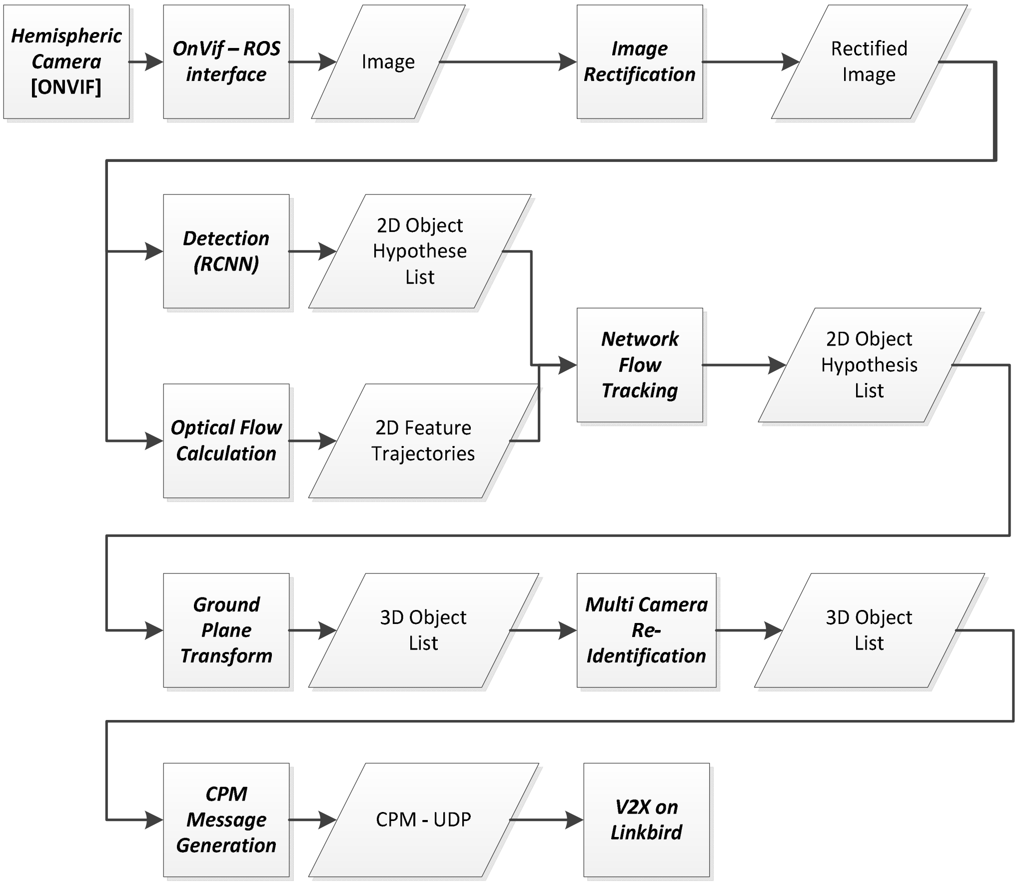

Figure 27: Building Blocks for the Hemispheric Camera Sensor Data Fusion

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

Figure 28: Capabilities of the traffic surveillance system based on the hemispheric camera. Top Left: Crowded Scene; Top Right: Pedestrian (#342); Bottom Left: Lorry; Bottom Right: Car with Trailer

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

DLR implements situation detection algorithms to support a strategy for mitigating traffic safety risks. Sensor data is used for estimating the risk. Measures to mitigate potential risks by the vehicle automation are not in focus. Given the spatial requirements of the Tostmannplatz in Braunschweig and given the scenarios in section 2.1.2, the following concept is proposed for use case 16: the infrastructure based detection system supports and extends the detection of traffic participants in the environment of the platoon. Additionally, potential risks and atypical events are estimated and detected by the infrastructure. Given the traffic rules and spatial features at the Tostmannplatz, a constellation where an infrastructure-based support system would help and where potential traffic conflicts are likely to occur is for left turning vehicles coming from the South direction. It is planned to use two cameras in order to detect potential conflicting VRUs and vehicles (see Figure 33). The field of view of these infrastructure sensors covers VRUs and vehicles coming from northern and western directions.
Regarding collision risk estimation between VRUs and vehicles there is groundwork and research related to right-turning vehicles and crossing cyclists [9]. By help of infrastructure-based object detection and tracking, the resulting trajectories are predicted and a Decision Tree is trained. The tree classifies conflict scenes for any situation at any time into 5 risk levels. Within MAVEN, this algorithm is adapted to the use case of left turning vehicles and potentially conflicting VRUs. Therefore, this work contributes to efforts to possibly generalize the approach.
The prediction of trajectories is essential for reliable risk estimation. Thus, a trajectory prediction algorithm is implemented using current motion and motion model according to the type of traffic participant (pedestrian, cyclist, car etc.) and historical trajectory data. Possible predictions are generated using an average template trajectory derived from past observations (Figure 29). Moreover, algorithms like Long-Short-Term-Memories (LSTM), which are state-of-the-art artificial neural networks (ANN), can be used for modelling time-dependent motion.
Depending on the risk level, the infrastructure sends out warning messages to the vehicle. It has not yet been entirely defined if this should be done by sending DENMs or SOMs.

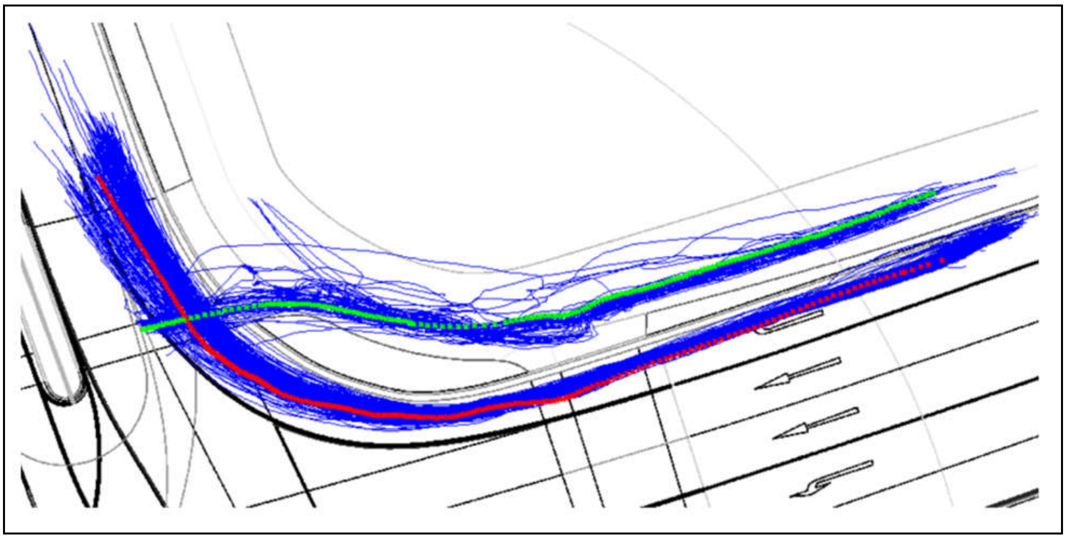

Figure 29: Template trajectory concept as the mean of trajectory observations in the past

DLR uses the **automated vehicles** FASCarE and ViewCar2 in MAVEN. The vehicles are equipped with LiDAR, Camera, Radar and Ultrasonic sensors (see Figure 30). The vehicle interface runs on the DLR software platform Dominion. The sensor data processing and sensor data fusion software is implemented in the Robot Operating System (ROS). ROS is widely

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

supported by the scientific community involved with automated driving research. Therefore, many cutting-edge algorithmic approached are available in ROS as software modules. This allows for the implementation of automated driving functions for a comparatively low effort.

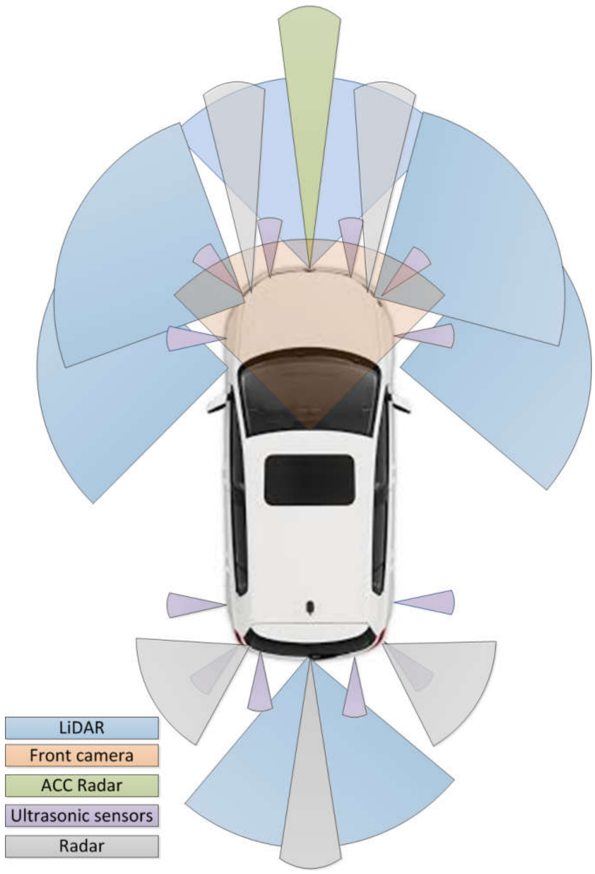

Figure 30: Sensor equipment of the DLR vehicle FASCarE

The functions implemented for sensor fusion **within the automated vehicle** are as follows (see also Figure 31):

- The system has an interface with the V2X transceiver.
- The system performs object detection in the Ibeo Lux LiDAR Sensor (Point Cloud Registration).
- The system has an interface with the ACC radar sensor of the car.
- The system performs Object Level Fusion for V2X CPM and CAM messages, LiDAR and ACC Radar.
- The system passes object lists from the LiDAR and ACC radar sensor on the V2X communication channel.
- The system detects VRUs and obstacles.
- The system predicts VRU trajectories and detects potential conflicts where the trajectories of the ego vehicle and the VRU intersect.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

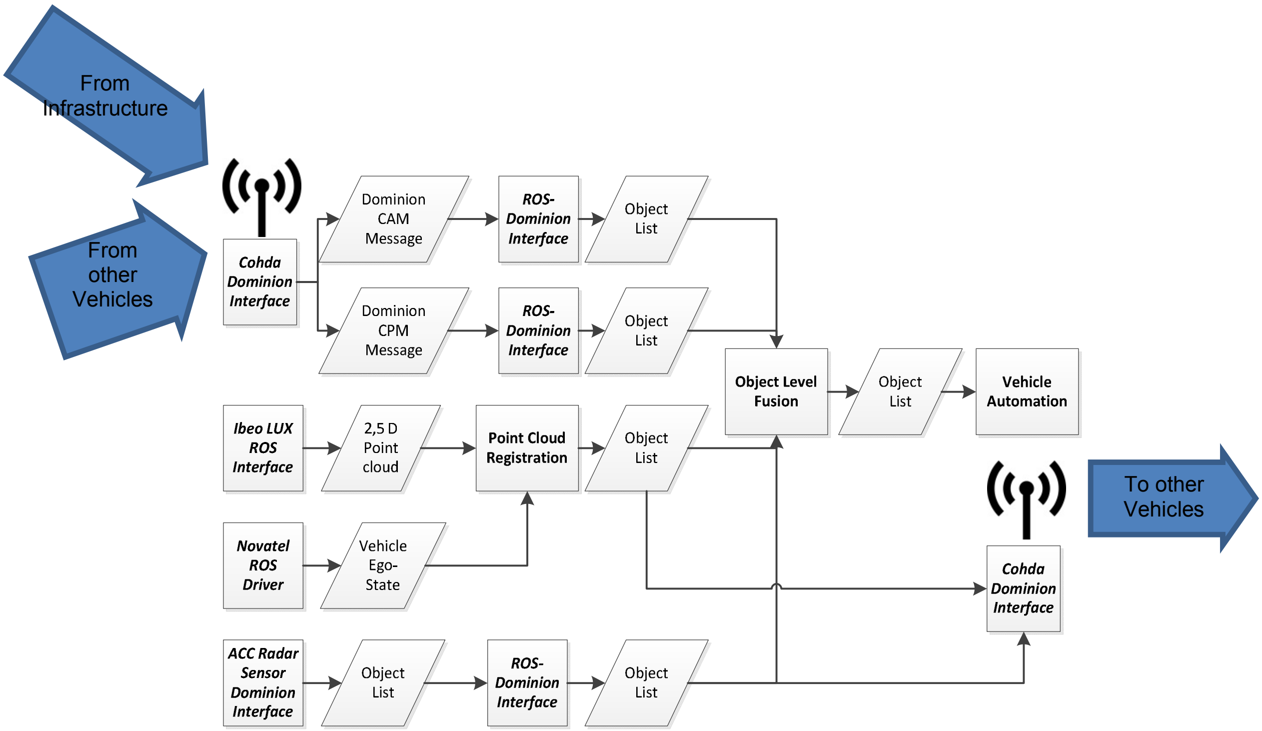

Figure 31: Building Blocks for the In-Vehicle Sensor Data Fusion

Similar to the infrastructure, the in-vehicle cooperative sensor fusion based on information shared by other vehicles and infrastructure provides a comprehensive view of the environment including static objects and road users. This view can be used to estimate collision risks with the highly automated cars. Within MAVEN the risk estimation algorithm is being implemented on the FASCarE and ViewCar 2.

The functions implemented for collision situation detection are:

- The system computes trajectory predictions.
- The system detects possible critical and uncritical encounters.
- The system contains a decision tree.
- The system supports right- and left-turning scenarios.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

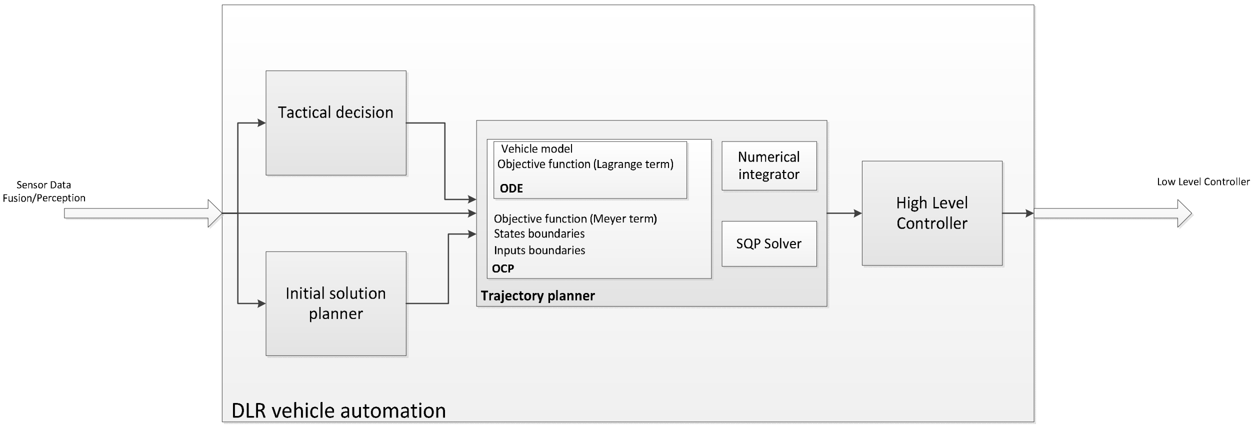

Figure 32: Vehicle Automation Building Blocks

DLR vehicle automation receives environment information from sensor data fusion as it is shown in Figure 32. As mentioned, this information includes local sensor data and fused CAM and CPM data. In addition, it also contains the locally available or received information about risky areas where trajectories are about to intersect, including the risk level. Based on this information, the tactical decision module defines a driving strategy and tasks for the trajectory planner. Objects and threats delivered by sensor data fusion are assigned with a certain confidence so that the tactical decision module is able to define dynamic tasks for trajectory planner based on objects confidence. A far object with low confidence results in a “soft reaction strategy” which is in most of cases driving slower and waiting for more accurate information about detected objects. On the contrary, a closer object with high confidence results in a “hard reaction strategy” which is mostly a braking or avoidance manoeuvre. Soft and hard reaction strategy is also used in case of collective perception. For example an object detected by other cooperative vehicles or infrastructure and still not detected by the ego sensors results in soft reaction (See Figure 4).

3.2.1.2 Evaluation method

The system evaluation will address the following research questions:

1) What is the impact of the different sensor data fusion strategies on the user experience?
   a) What are the strengths and weaknesses of incorporating V2X data in the sensor data fusion compared with the baseline system?
   b) How does a system equipped with V2X sensor fusion compare with the baseline system with respect to reliability and precision?
   c) What are the specific challenges attributed to cooperative perception?

2) What are the design considerations for the data fusion algorithms?
   a) What is the frequency of situations where the different data sources of sensor fusion (infrastructure, CAM and CPM) diverge and/or give contradicting detections?
   b) How is the optimal fusion strategy in situations where sensor detections of the different data sources diverge or contradict?
   c) What is the robustness of the cooperative perception system in case of contradicting sensor data?
   d) How do the sensor fusion approaches for track level fusion (for more detail, refer to MAVEN D3.1) compare with respect to reliability and precision?

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors’ view and the European Commission is not responsible for any use that may be made of the information it contains.

e) To which degree sensor fusion will decrease uncertainty in the system?
f) Is the sensor fusion result with cooperative perception unbiased or is there an estimation bias rendering the approach being worse than accounting for in-vehicle sensors only?
g) There is a time delay in the processing chain of the different data sources. CPMs and CAMs from the road users usually do not take more than 200ms from detection to message delivery. CPMs from the road side infrastructure need 400ms to 1s for this process. What is the most effective strategy to deal with this problem?
h) What is the degradation of the information content vs. delay for infrastructure CPMs?

3) How well can road user trajectories and conflict situations be predicted?
   a) What is the amount of historical trajectory data needed for meeting performance goals?
   b) How do different types of algorithms compare with respect of error metrics?
   c) What is the false alarm rate (true/false positives) for the detection of critical situations?

The system is first evaluated during the Integration Sprint 4 (currently ongoing at the time of writing this document) on the one hand on the Tostmannplatz in Braunschweig. The reaction of the automated vehicle to CPMs and especially in terms of VRU detection is tested in advance on the Edemissen and DLR test tracks. The general setup of the Tostmannplatz evaluation scenario is shown in Figure 33. The automated vehicles FASCarE and ViewCar2 are crossing the Tostmannplatz and receiving CPMs from the infrastructure and from each other. Evaluation includes the recording of data into log files in ROS bag format. Based on the log files, evaluation is based on a comparison of the performance of the different methods under consideration with a ground truth and/or an offline low level fusion baseline. As performance indicators, precision, reliability and the frequency of false positive and false negative detections of objects and critical situations (confusion matrix) are used.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

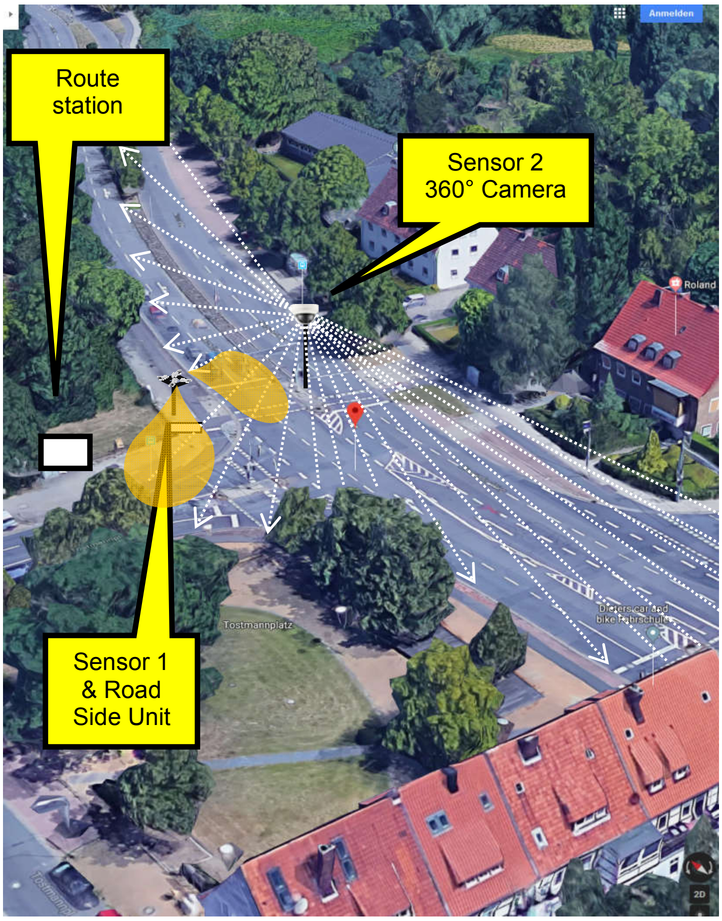

Figure 33: Braunschweig test site Tostmannplatz. Orange areas mark focus areas for VRU detections (visualized on GoogleMaps)

3.2.1.3 Evaluation results

Evaluation results will be included in D7.2 as the studies are ongoing during creation of this document.

3.2.2 Handling non-cooperative vehicle interfering with platooning AD vehicles

3.2.2.1 Functional behaviour

The scenario described in section 2.1.1 is handled in a consecutive order of steps. First, the vehicle on the other lane has to be detected. Then, the intention of changing the lane has to be estimated. This estimation can either be done by taking into account the vehicle movement or indicator signals, or by taking into account the situation (e.g. road topology, obstacles, etc.).
As this is a complex topic requiring a lot of effort and various different approaches, it has been decided to investigate intention estimation only by indicator setting or by a road topology with merging lanes.
The functions implemented for detecting the indicating platoon breaking-up vehicle within the sensor fusion of the automated vehicle are as follows:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

- The system has an interface with an on board camera and records image data.
- The system detects road users in front of the ego-vehicle and their turn indicator status.
- A status message is generated upon detection of the turn indicator "on" status. Within the sensor fusion, the vehicle is marked as "indicating". This information is forwarded to the vehicle automation and to the filtering module responsible for sharing the object data via V2X (see Figure 26). Please note that currently only the object data itself can be shared using CPM, as the vehicle light status is not part of the CPM right now.

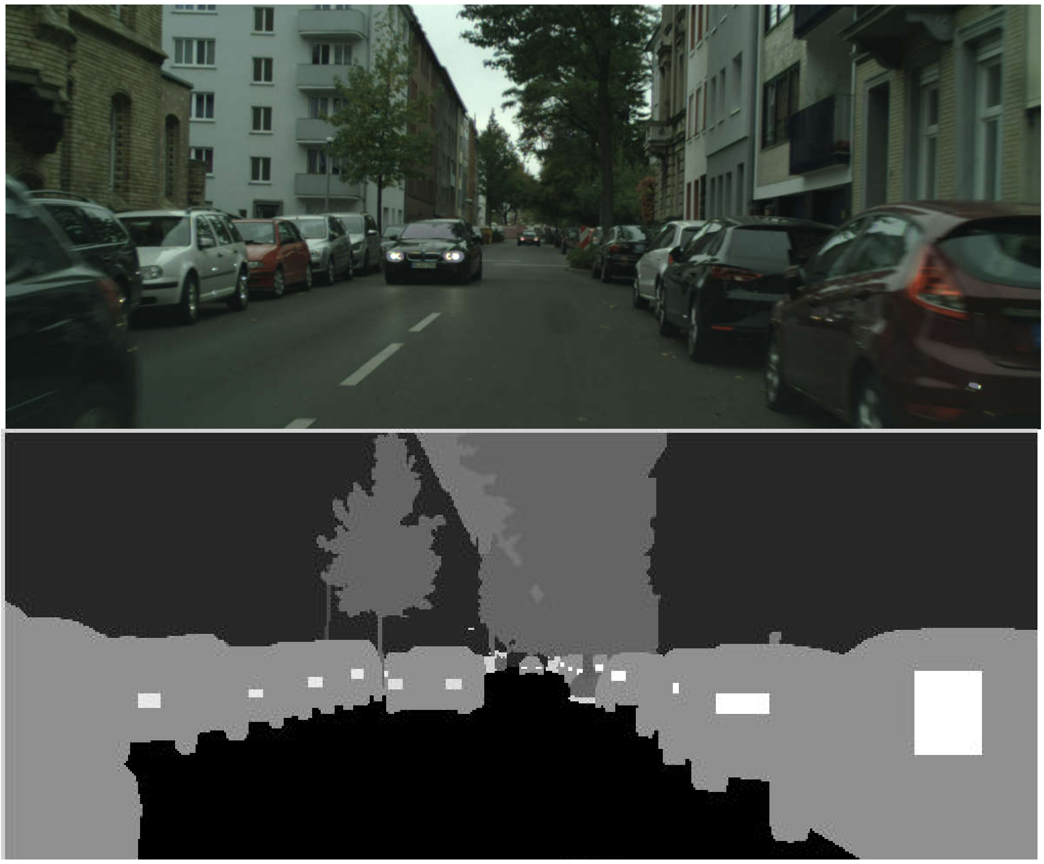

Figure 34: ANN-supported turn indicator status detection using semantic segmentation. Top: input image with road users. Bottom: detected areas containing turn-indicators

After the detection of the vehicle object and the deduction of the lane change intention by indicator signal detection, the vehicle automation is receiving this information. It is directly forwarding this information to the Platoon Logic. While the Platoon Logic will be described in detail in D3.1 and has already been described partly in [7], it basically consists of a set of state machines, shown in Figure 35.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

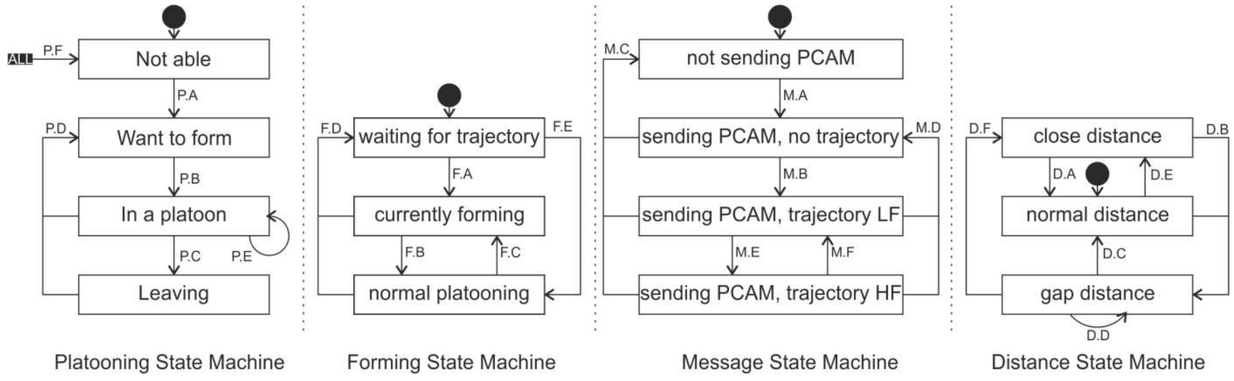

Figure 35: The four different state machines used for platooning

The most important part of the state machines in context of this deliverable is the Distance State Machine. It basically controls the desired distance of the platooning vehicles individually. According to the state of this state machine, the distance to the preceding vehicle can either be “normal”, “close”, or a “gap” for allowing other vehicles to join the driven lane. While driving in a platoon, “close distance” is set. The Platoon Logic will trigger opening a gap whenever there is a vehicle on the adjacent lanes:

- With its tail within a given range from own tail to preceding tail (blue area in Figure 36) or its front within a given range from own front to preceding front (orange area in Figure 36),
- Which is driving in the range +/-10% of my own velocity,
- Which is intending to change the lane

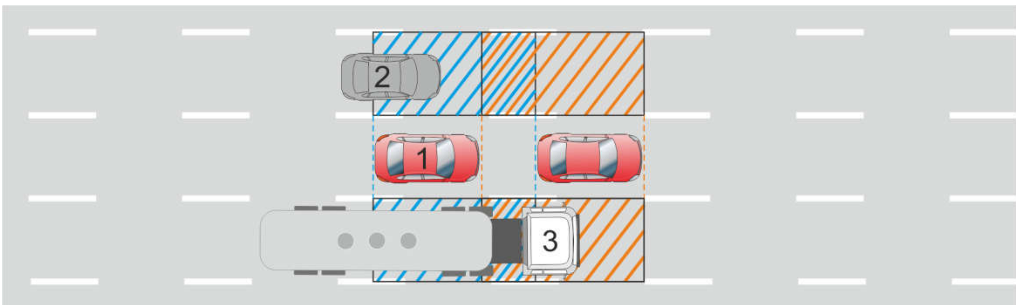

Figure 36: Ranges around vehicle 1 in which another vehicle is considered as candidate for a lane change to Vehicle 1’s lane. As the range is in relation to the tail of the other vehicle, Vehicle 2 is not a candidate. The truck 3 is a candidate, because its front is in the orange area.

As all of the required information is available locally in the ego AD vehicle, the state machine is able to trigger the state of opening a gap. This information is directly forwarded to the trajectory planner of the vehicle which is responding by planning corresponding actions.
If the road topology is the reason for vehicles to change the lane (like in Figure 37), the simple object data of the vehicle is sufficient for the vehicle automation to detect this intention by mapping the vehicle object data to the available HAD map lanes. When the lane of the platoon and the adjacent lane are merging ahead, the vehicle intention is internally set, resulting in the corresponding Distance State Machine transition to open a gap and the related behaviour of the trajectory planner. For this, also objects perceived via CPMs are taken into account.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors’ view and the European Commission is not responsible for any use that may be made of the information it contains.

Figure 37: Merging areas on the Tostmannplatz in Braunschweig (visualized on GoogleEarth)

3.2.2.2 Evaluation method

System evaluation will address the following research questions:

1) How reliable can the status of the turn indicator be detected? What is the influence of weather and lighting conditions?
2) Pre-tests show that the reliability of detecting a situation where a non-cooperative vehicle is interfering with platooning vehicles is poor. Can the reliability be improved by adding information about lateral dynamics of the platoon break-up vehicle?

Furthermore, the functionality of the Distance State Machine needs to be evaluated as well as appropriate timing for opening the gap and resulting distances to the preceding vehicle. This includes situations where the intention is interpreted by detecting the indicator signal and by matching the vehicle object positions to merging road segments.

3.2.2.3 Evaluation results

As according to the WP6 integration sprint schedule the testing of platoon behaviour will be done in the 5th and 6th integration sprint performed from September 2018-February 2019, evaluation results will be shown in the upcoming deliverable D7.2.

3.3 Dynniq developments

The use cases and its requirements have been introduced in Chapter 2. This section will focus per use case on the functional behaviour, the evaluation method and preliminary results when available.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

3.3.1 Lane advice when VRU is detected to interfere with unprotected right turn using LAM message

3.3.1.1 Functional behaviour

This use case has two main objectives: increase traffic safety and increase traffic efficiency. Safety is improved by reducing stops that always have a risk of rear-end collisions. These will not occur with the automated vehicle itself as it has good sensors to detect a stopping vehicle ahead, but may occur to non-automated vehicles behind that don't expect the stop ahead. In general, this use case will make lane changes occur more in advance and smooths acceleration and deceleration behaviour. These effects are all expected to increase safety. For traffic efficiency, redistributing vehicles in order to let them pass the intersection quicker has the advantage that the green phase can be shorter leading to shorter waiting times for conflicting traffic.
From an implementation point of view, this use case requires several algorithmic components. The first is the detection of the VRUs, from which a prediction needs to be derived when the intersection area is blocked for right turning vehicles. This is illustrated in Figure 38:

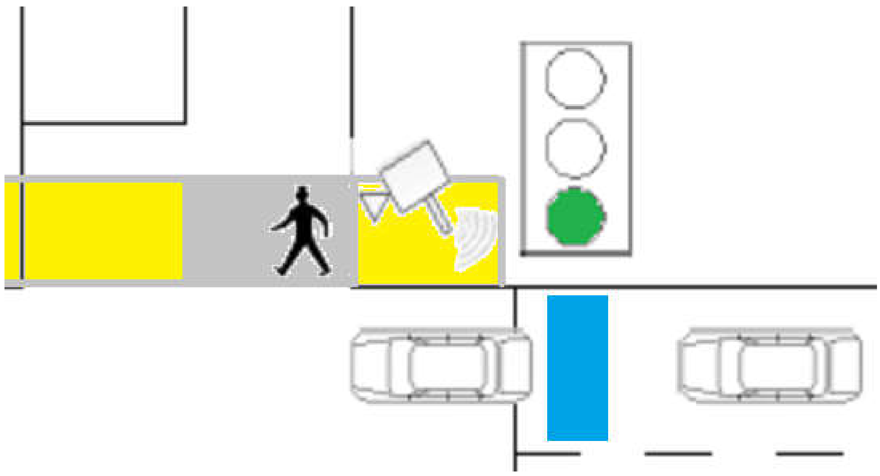

Figure 38: Conflict area predictive monitoring

VRUs will be monitored in the yellow areas to track their speed and direction in order to predict whether they will arrive in the grey conflict area during a green phase. This same movement is extrapolated for determining up to when the VRU will be in the conflict area. While in the grey area the speed will be tracked as well to update the moment the VRU will leave the area. The yellow areas are on both sides to account for bidirectional VRU movements over the conflict area.
The second component is vehicle monitoring and prediction. This can be based on infrastructure sensors, but also on intended turn direction information included in the MAVEN extended CAMs received by cooperative AD vehicles [5]. This follows a hierarchical approach:

- The blue rectangle in Figure 38 indicates the stop line detector that is a presence detector and is expected to generate pulses of occupied/unoccupied status as vehicles pass over it. When this pattern is interrupted (either by a detector remaining occupied or unoccupied for a longer period of time) while there are still vehicles in the queuing model of the traffic light controller, it means there is a vehicle waiting for a crossing VRU.
- Vehicles transmitting a CAM message can also be detected as stopped.
- The vehicles on the approach towards the intersection were already detected by loop detectors upstream. However, their turn direction is not known by the traffic controller. Their turn direction will be estimated based on historical turning ratios.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

- Approaching cooperative AD vehicles will transmit the MAVEN extended CAM message and, through this, their turn direction and lane is known. These vehicles will have the estimated turning percentages overwritten by the known values (explicit probing).

The third and last component is the lane advice algorithm itself, which follows the steps according to Figure 39.

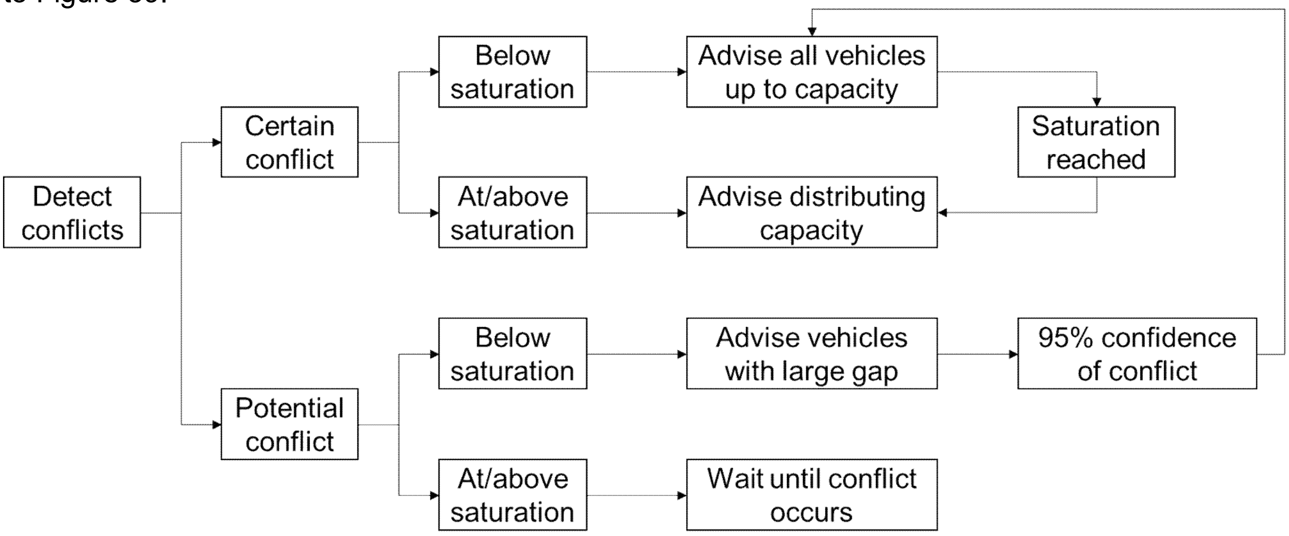

Figure 39: Lane advice algorithm design

- Compare the (predicted) VRU conflict area occupancy with the queued and arriving vehicles to identify the chances that a vehicle will have to stop to turn right (this check is repeated at a 1Hz frequency)
- From this, either a potential conflict (according to turning percentage) or a certain conflict is detected. This is when a stop has already been detected or when a vehicle indicates its intended turn direction with the MAVEN CAM message.
- The next step is the saturation level of the approach. Here it depends whether the approach is below saturation or not and if the conflict is certain or not.
    - In case of a certain conflict, all approaching vehicles will get advice to switch lanes. This even continues once the saturation of the other lane is reached. In that case drivers will have to find a space themselves to switch lanes and are likely to slow down the vehicles on the target lane because they have to make space.
    - When there is a potential conflict and the target lane is at saturation, the algorithm will not trigger. When it is below saturation, only vehicles that have a large gap and can merge without disturbing other traffic for certain will be advised to change lanes. At the same time, the queue model predicts into the future enabling vehicles further upstream to obtain advice. Once the chance of a conflict occurring exceeds 95%, it is treated as a certain conflict and the other logic will apply.

3.3.1.2 Evaluation method

Since the use case has objectives for both safety and traffic efficiency, both will be evaluated. The following parameters will be measured via simulations:

Table 1: Evaluation measures for lane advice

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

Measure	Description
Collisions	Expected to be zero both in baseline and with the MAVEN system on, nevertheless it is good to keep as a control.
Time to Collision	A direct safety measure, the lower this value, the more dangerous a situation is. However, values within the default car following/platooning should be excluded.
Maximum deceleration	Strong deceleration is an indication for danger; only values larger than the deceleration for stopping at an intersection should be tracked.
Average acceleration/deceleration	This measures the fluency of the traffic; the absolute value of acceleration/deceleration will be tracked. Lower values indicate better fluency.
Throughput	The total number of vehicles that passed through the simulation network. If this value is significantly lower, the other traffic efficiency indicators are not valid and either the control strategy or the traffic demand needs to be recalibrated.
Average delay	The average delay incurred by vehicles as compared to their theoretical free flow travel time. This is a better indicator than waiting time because the time lost accelerating/decelerating is also included. It is also better than travel time, which is difficult to place in perspective because a large part of the distance is travelled under free flow conditions.
Average stops	The average amount of times a vehicle has stopped to pass the intersection. Apart from discomfort and a risk of rear-end collisions, this is also an indicator for environmental pollution as stopping and reacceleration have a high impact on the environment.
Total CO_2 emissions	In simulation it is possible to determine the CO_2 emissions from all vehicles. However, it should be noted that this measure has the same problem as the travel time measure and includes many emissions not influenced by the system. The value should go down, but may only go down slightly.

These measures can all be acquired via simulations. With the field trials, the traffic safety and efficiency measures cannot be obtained because not all traffic participants are V2X equipped and tracked, and only one AD vehicle is adopted (the Hyundai AD vehicle). Nevertheless, the motion profiles of the AD vehicle used for testing at the Helmond test site can be analysed after the tests. This analysis will allow retrieving, when possible, real world inferences that can enrich the results obtained via simulations. The mentioned tests will be executed during the last integration sprint (happening after the submission of this document).

3.3.1.3 Evaluation results

The results from the real road implementation will be included in D7.2, as street deployment is planned in February 2019 at the end of the last integration sprint. Simulations will be carried out in WP7 as well.

3.3.2 Lane advice for queue distribution at signalized intersections

3.3.2.1 Functional behaviour

Similar to the previous section with lane advice for unprotected movements, this scenario focusses on both safety and traffic efficiency. The objectives are the same, but the safety effects are less pronounced as the queue can be easily foreseen by the traffic light state visible by all traffic

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

participants. Nevertheless, a large imbalance between the size of the queues on two lanes can still have a negative effect on safety. The effects on traffic efficiency are more pronounced because the situation is more predictable.
As already explained in D5.1 [5], the MAVEN project has profiled the Signal Phase and Time (SPaT) message is a way to allow lane-dependent speed advices using MAP/SPaT messages. The SPaT defines zones with speed advice in the form of speed-distance pairs. A vehicle can determine its distance to the stop line with this advice and compare the advice of different lanes. In theory, the lane with the lowest advice should be the optimal lane to choose. However, when more than two vehicles follow such an advice, there is a high probability for oscillations to occur as demonstrated in Figure 40. In the subfigure A three vehicles are approaching intersection on the right lane (grey vehicles). The original queue at the stop line has 4 vehicles on the right lane, and 3 vehicles on the left one. In the subfigure B the speed advice on left lane has a higher value, so all vehicles switch lane. The first grey vehicle is the 4th in the queue of the left lane and would be the 5th if it switched back, so for this vehicle the speed advice is higher on the left and the vehicle will stay. The 2nd grey vehicle would be the 5th vehicle on both lanes and therefore the speed advice for both lanes is equal, this would not result in a lane change. The last vehicle, however, is the 6th on the left and the 5th on the right. The speed advice will be higher on the right and the vehicle switches again as is shown in Figure 40C. In summary, the last vehicle switches lanes twice and will also overtake the second last vehicle on the right. Despite most countries allowing this when traffic is queued up, it is still an undesirable situation.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

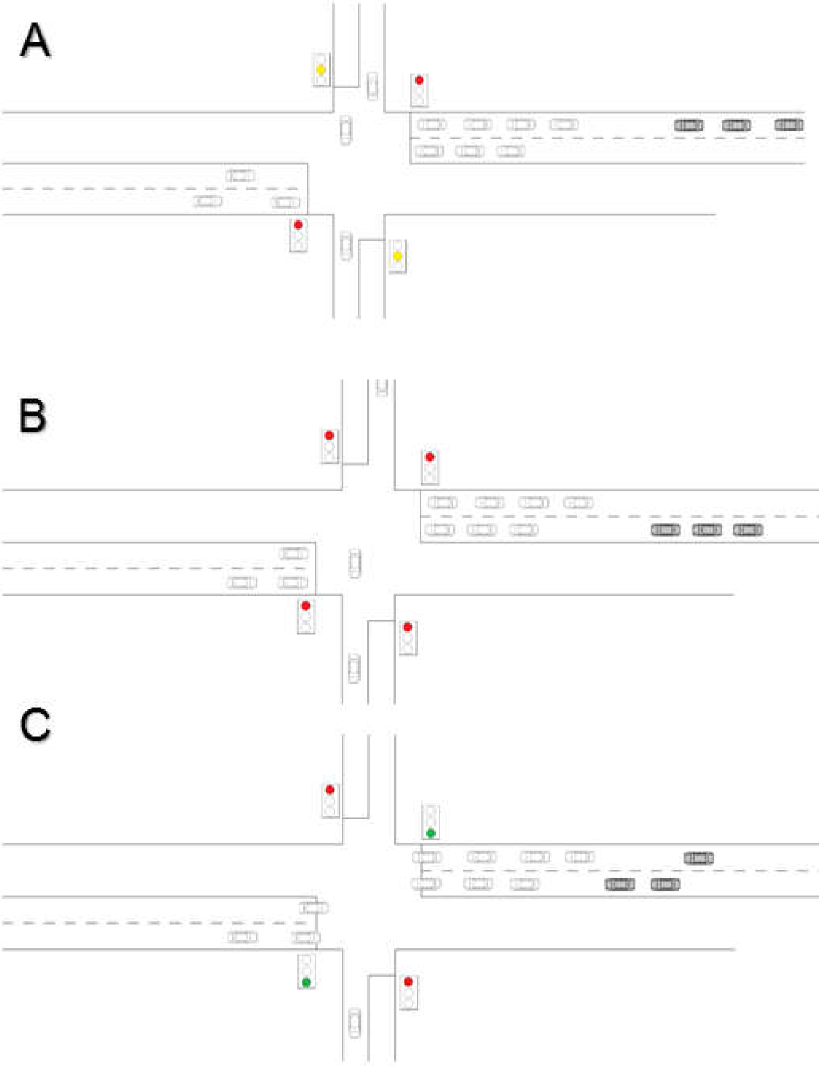

Figure 40: Oscillations as a result of lane advice derived from SPaT

With the LAM message, the infrastructure can coordinate the lane changes and process them in the same order as the vehicles would arrive at the intersection, resulting in the following workflow:

1. Determine the optimal lane for the first grey vehicle, resulting in an advice to the left lane.
2. Assuming the first vehicle respects this advice, determine the optimal lane for the second vehicle, resulting in no advice.
3. Determine the optimal lane for the third grey vehicle, considering the first follows the advice and the 2nd stays on the same lane. This results in an advice to the left lane.
4. Encode the advice to both vehicles in a LAM message and broadcast this.

The situation starts the same as in Figure 40a, but instead of two phases of lane changes, there is only one resulting in the situation shown in Figure 41.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

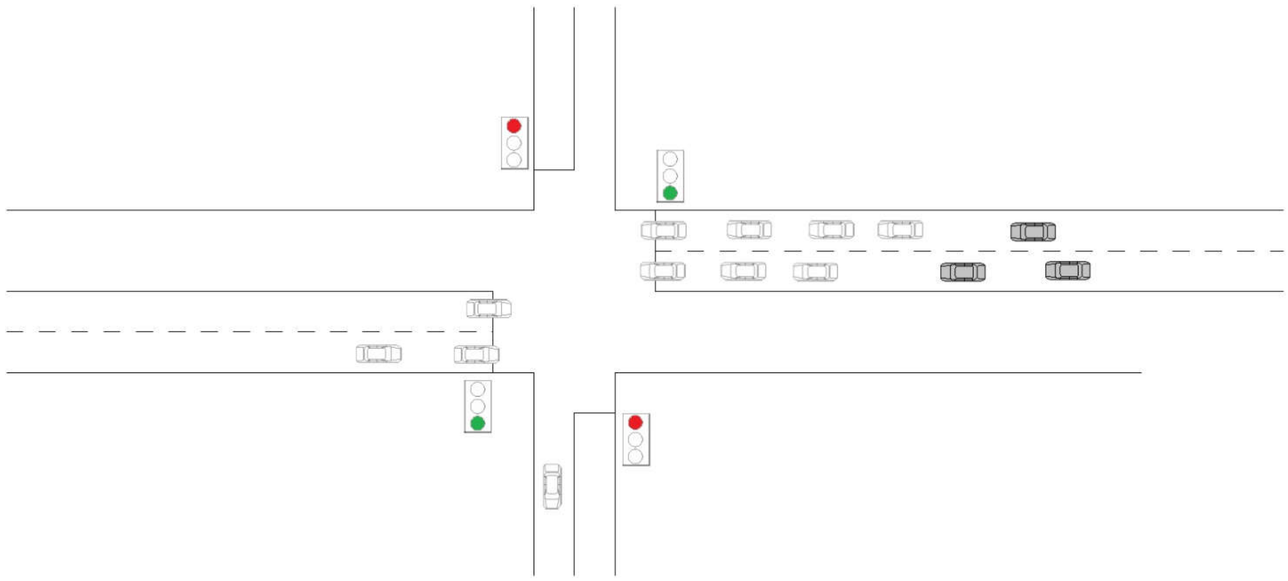

Figure 41: Vehicles approaching the intersection after implementing advice of LAM message

Since the vehicles reach their final lane quicker, the third vehicle is already overtaking the second. This makes the speed advice in the SPaT message more effective.

3.3.2.2 Evaluation method

The evaluation uses the same measures as presented in Table 1. Again, in simulation all measures can be acquired, while the field trials will be limited to analysis of the AD vehicle motion profiles exactly as described in Section 3.3.1.2. The mentioned trials at the Helmond test site with the Hyundai AD vehicle will be executed during the last integration sprint (happening after the submission of this document).
Besides, LAMs are also implemented on Tostmannplatz by DLR. There, a SUMO simulation runs with real car data acquired by loop detectors placed on the road and by CAM reception (see D6.2 [36] for details). In SUMO, the queue length can directly be accessed. According to the provided values, LAMs are generated in a coordinated way. This will also be tested during the last integration sprint.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

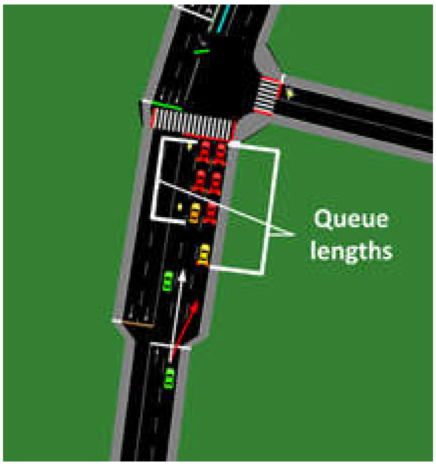

Figure 42: Queue length estimation on Tostmannplatz using SUMO simulation, done by DLR

3.3.2.3 Evaluation results

The results will be included in D7.2 as street deployment is planned in February 2019 at the end of the last integration sprint. Simulation will be carried out in WP7 as well.

3.3.3 Intersection control enhancement by vehicle probing

3.3.3.1 Functional behaviour

As introduced in Section 2.2, the additional probe vehicle data acquired with the MAVEN CAM extensions open new possibilities for the traffic light controller. This section explains the behaviour of this use case by applying it to the Helmond test site.
Typically, a multi-lane approach to an intersection will consist of several movements that do not necessarily need to be assigned green within the same stage. For instance, consider a stage diagram as depicted in

Figure 43. A commonly encountered configuration is to assign the right-through movements of the same direction to the same stage, and the left-turn movements of the same direction to a separate stage, as they are in conflict with the through movements, but not with each other. Now, let us assume that the intersection is equipped with an adaptive stage planning algorithm, and the demand is detected by inductive loops located at the entry of the approach. Our case study will be the intersection of Europaweg and Hortsedijk, which is generously equipped with inductive loop detection, both at entry links and at stop lines. From now on, we will refer to this intersection as HEL701.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

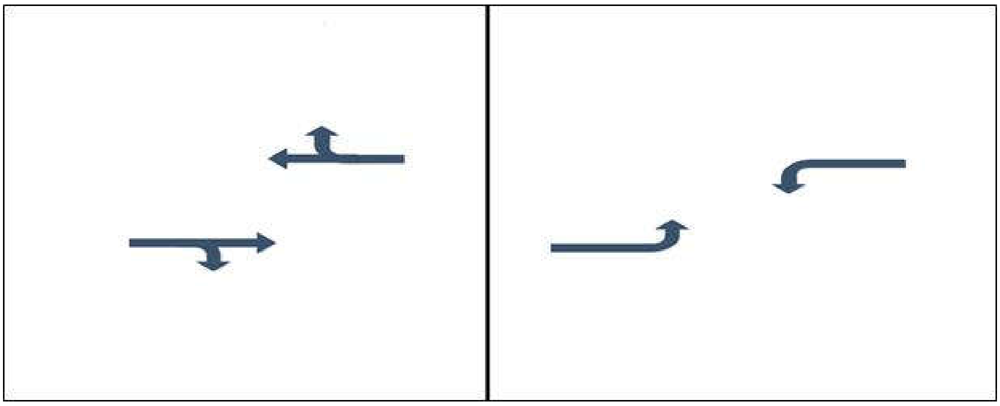

Figure 43: Phase diagram for the East-West direction at HEL701

Consider the eastern approach to HEL701, depicted in Figure 44. Vehicles following this link have two lanes at their disposal. The link entry detectors are located at the distance of approximately 400m from the stop line, near the upstream intersection HEL702. At the distance of approximately 150m to the stop line, the link splits into four lanes, with two lanes belonging to through movement, one to right movement and one to left movement.

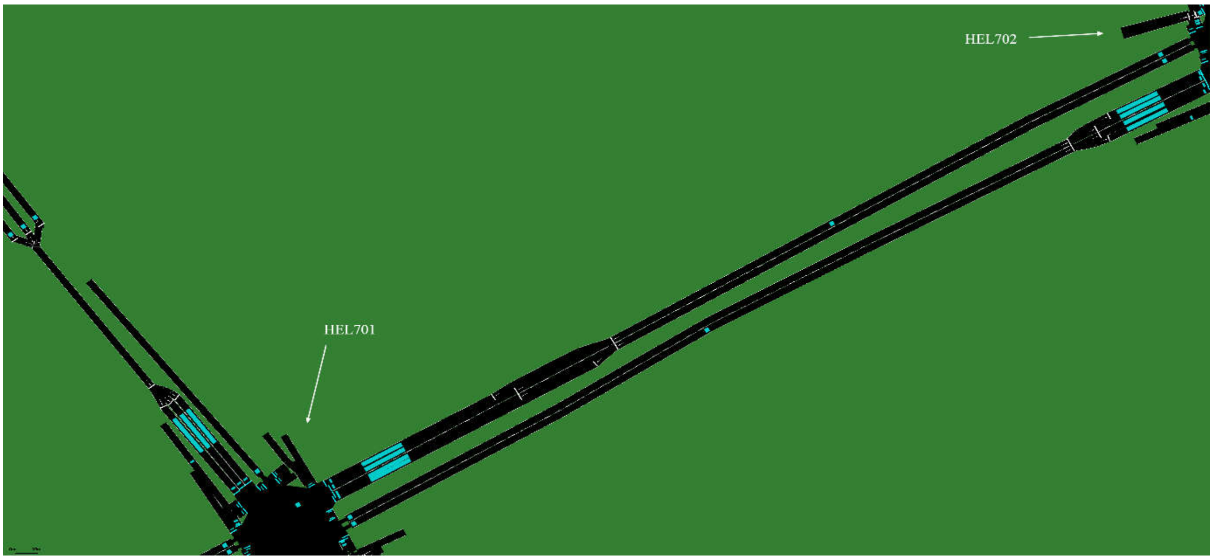

Figure 44: Approach from HEL702 to HEL701

This configuration poses a challenge to the adaptive traffic light controller equipped solely with inductive loop detection. Let us suppose that a detection event occurs at the entry link. The planning module in adaptive traffic light controller needs to determine, which stage can be given to the detected vehicle, and at what moment, so it is dispatched in a most efficient manner. However, real-time information about the movement direction and the velocity of the vehicle is not available directly from the entry link inductive loop reading. The movement direction can be read from inductive loops usually only when the vehicle leaves the intersection and passes one of the loops positioned at the stop line. The only exception is when the vehicle is the first in a queue, then it is stopped at the induction loop and the algorithm knows that there is at least one vehicle waiting. In

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

all other cases, the algorithm has to estimate based on historical turning percentage averages. This introduces inaccuracy and can result in suboptimal stage planning.
Such situation is depicted in Figure 45. Based on turning percentages, the traffic light controller estimates that the vehicles will follow the arterial road and gives green to the through movement. However, in our situation all vehicles decide to turn left, and in consequence stop at red. A cooperative AD vehicle using the MAVEN CAM extensions can circumvent this problem by transmitting their movement position. In Figure 46, a MAVEN CAV informs the intersection about the lane it is following, and receives green for the left movement.

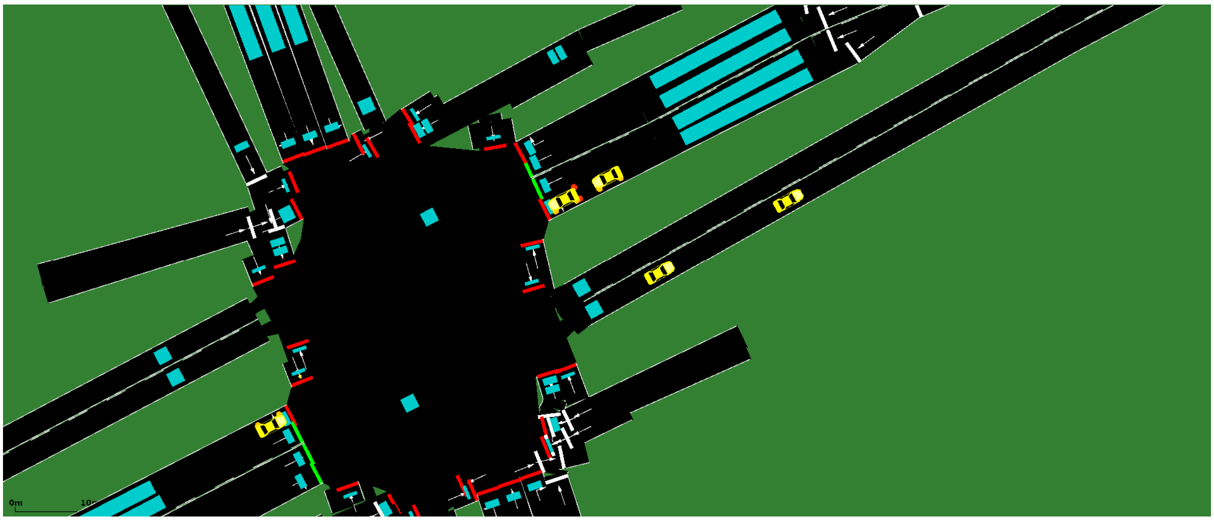

Figure 45: Non-cooperative vehicles can arrive at the stop line on a different movement than predicted

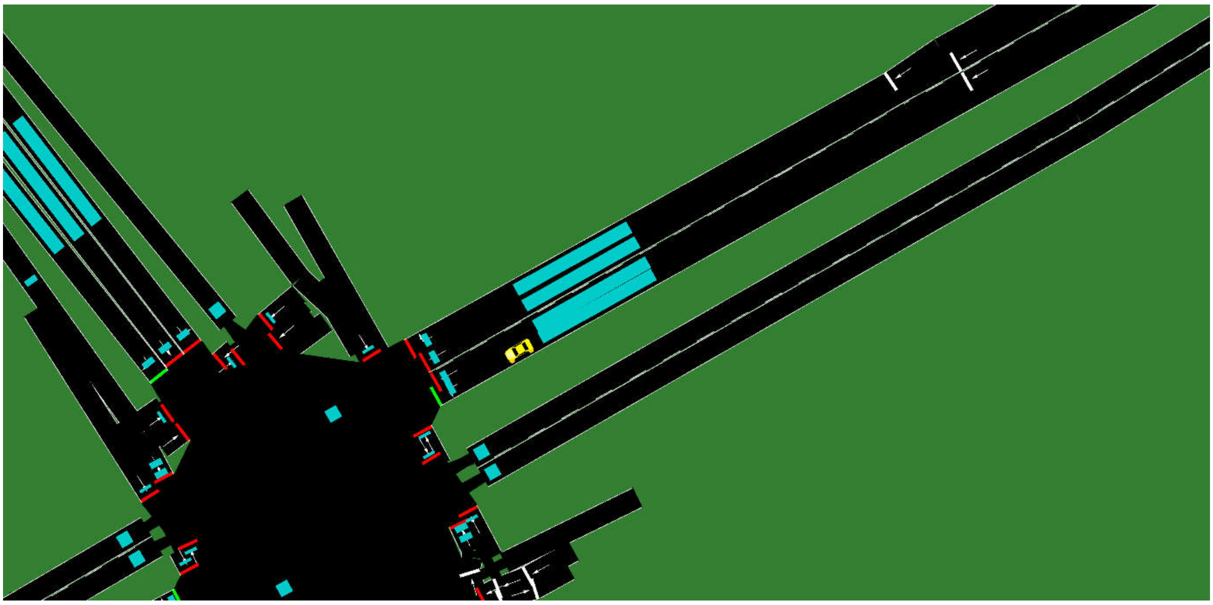

Figure 46: A MAVEN CAV transmits its lane information and receives green in advance

Similar challenges arise when estimating the velocity of the vehicles. The speed limit for the link is often a good approximation. However, certain special or heavy-duty vehicles in urban conditions

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

will not be able to reach this speed. A wrong prediction in their arrival time can result in wasted green time and an unnecessary stop. MAVEN CAVs equipped with cooperative transmission systems can communicate their position and velocity values to the controller, so a late arrival can be predicted and taken into account during signal planning.

3.3.3.2 Evaluation method

To evaluate the impact of the improved detection, we have performed traffic simulations on a network representing a part of the arterial road N270 passing through Helmond. The network consisted of seven consecutive intersections controlled by the adaptive algorithm ImFlow, one of them being HEL701, the intersection mentioned in the previous section. It is worth noting that the same algorithm is deployed to control the intersections in the reality. A standard mode of operation of the control system is to predict queues based on inductive loop detection. We compared it with the custom version enabled with queue detection based on real-time probe vehicle data, collected at 1Hz frequency.
We tested three configurations. In the baseline scenario, we assumed that all detection is based on inductive loops, and that all vehicle approaches are equipped with entry loop detectors. In the first CAV scenario, the RSU was configured to receive probe vehicle data on the approach from HEL702 to HEL701. This scenario can represent a situation where a link approach is dedicated to cooperative automated vehicles (CAVs). In the second CAV scenario, probe vehicle data was transmitted on all approaches to HEL701. For CAVs, MAVEN extended CAMs were assumed to contain information about the reference position, the lane position and the velocity of the vehicle, supported by CAMs according to the most recent ETSI specification [38]. Additionally, the intended turn direction in the form of the signal group from the MAVEN CAM extension was also included [5][6]. For deployment, a translation can be done at the receiving side of RSU, when only ingressing lanes are received. In the case of the last part of the HEL702 to HEL701 link it is depicted in Table 2 (lanes counted from the right).

Table 2: Lane to movement translation table for the HEL702 to HEL701 link

	Lane 1	Lane 2	Lane 3	Lane 4
Right	✓	✗	✗	✗
Straight	✗	✓	✓	✗
Left	✗	✗	✗	✓

For all three CAV penetration rate scenarios, the total traffic volume was based on actual demand data provided by the municipality of Helmond for a typical evening peak hour. The approach HEL702 to HEL701 was a part of the arterial road, which had approximately 5 to 10 times higher demand than the demand on the side roads.

3.3.3.3 Preliminary results

The results were evaluated using the method implemented and described in [39]. After 10 simulation runs of 2 hours each, we compared the average delay (in seconds) and the average number of stops per road user at the intersection 701, and aggregated both of these numbers in a single indicator value *impact* of dimension seconds. Originally, the metric of impact was defined in [40] as the average number of stops of road users at a single intersection passage multiplied by 8

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

and summed up with the average wait time. We applied the Bessel's correction to calculate the standard deviations. The results are summarized in Table 3 below.

Table 3: Traffic performance results

	mean delay (s)	std. delay (s)	mean stops	std. stops	mean impact (s)	std. impact (s)
Baseline	24.052	0.780	0.657	0.021	29.312	0.727
Coop. HEL702 to HEL701	24.207	0.890	0.655	0.020	29.451	0.792
Coop. All to HEL701	21.917	0.296	0.692	0.013	27.456	0.381

Taking into account the standard deviations, we did not observe noticeable differences comparing the baseline scenario with the scenario where additional detection is enabled at a single approach. However, with cooperative detection enabled for all vehicle links the improvement becomes apparent. Compared to the baseline, the delay time was reduced by approximately 9% and the impact by approximately 6%.

An increase in the number of stops of about 5% was observed, this was likely due to the TLC optimizer forfeiting rewards in stops in favour of rewards for the optimization objective of combined delay and stops. The calibration of the algorithm was deliberately not adjusted with respect to the baseline to allow for a fair comparison. However, due to inaccurate information certain measures had to be taken in the calibration to be more robust against queue length estimation errors. The relatively low importance of stops is the most important here. It is inefficient for the controller to extend the green light for a potential vehicle that may arrive, but may also arrive in a different lane for another turn direction that is not green. With better information the optimizer is more effective at optimizing for delay, which is at the cost of stops, because it has a lower importance than in the evaluation metric.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

4 HAD map extensions implementation and evaluation

This section describes the results of the required MAVEN HAD extensions implementation as well as the evaluations made by the interested partners on the top of them.

4.1 MAVEN extended HAD maps format

The Braunschweig HD Map sample has been delivered in a shape file format and accommodates a model of the intersection for the Tostmannplatz area. This model includes the additional features as defined in Section 2.3.2 like stop lines, pedestrian crosswalks and start and end of corridors to support the MAVEN use cases. All other intersections in this HD Map sample are ignored and continuous lane groups, centrelines and lane borders are provided instead.

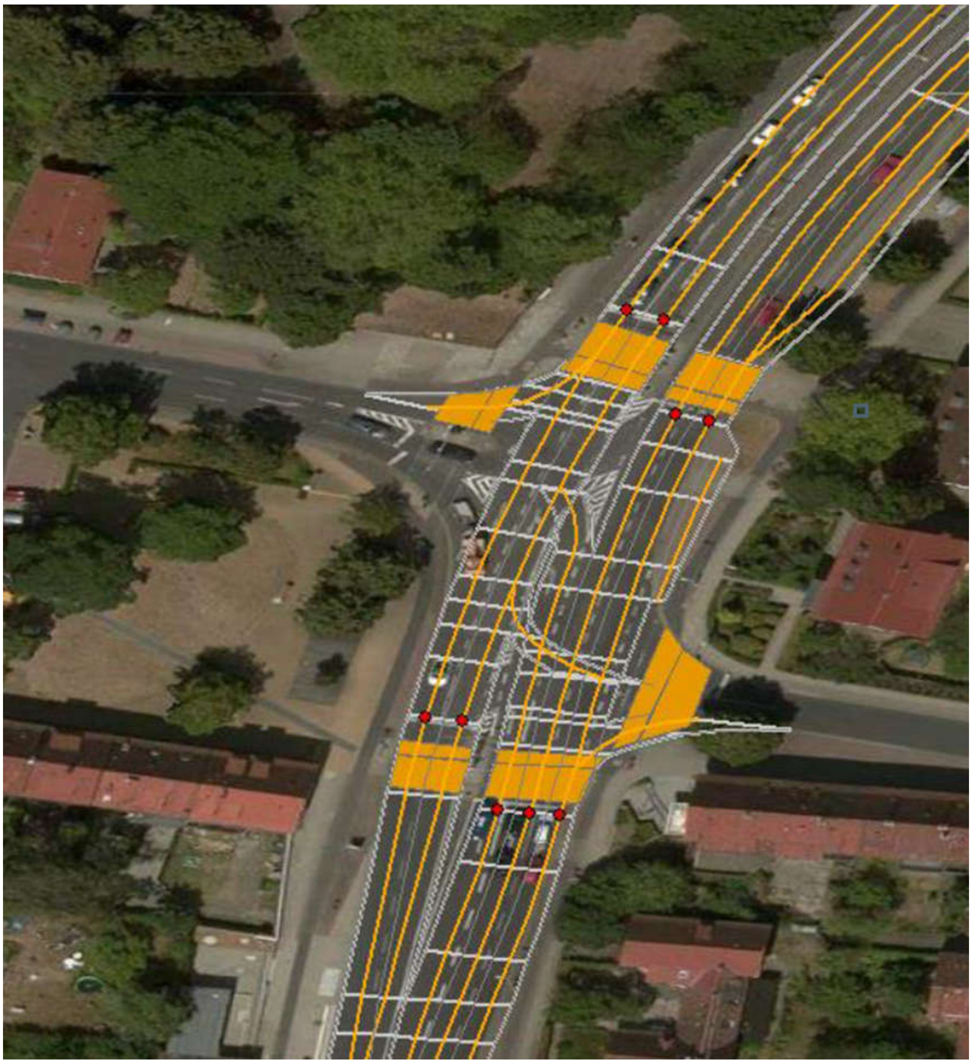

Figure 47: MAVEN extended HAD map format for the Braunschweig Tostmannplatz (visualized on GoogleMaps)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

4.2 Hyundai evaluation results

As mentioned in Section 2.3, the objective of the MAVEN extended HAD map evaluation is to demonstrate that the new format can reliably support computation of vehicle trajectory and control as a result of providing map points that accurately adhere to the actual road profile, as well as a complete set of information for the need of AD algorithms.
For the specific case of the Hyundai AD algorithms for planning, decision and control modules, the MAVEN extended HAD map format fully provides the required set of information. Without entering in the technical details of these algorithms, it is sufficient to mention that while moving in automated mode, the planned trajectory is iteratively recalculated in such a way to follow as good as possible the centre line of the lane along the currently considered source-destination route. Additionally to this functionality, the system performs a threat assessment that looks at possible obstacles in the currently driven and planned lanes to influence manoeuvring decisions (decelerate/brake, abort a possible lane change, etc.). In order to perform this threat assessment, the system needs to know, along the entire route, the precise coordinates of the HAD map lanes boundaries. Thanks to the MAVEN extended HAD map format, this threat assessment is now also possible at intersection areas because of the presence of the “intersection corridors” defined in Section 2.3 and shown in Section 4.1. Moreover, the AD system needs to know where to stop at intersections because of presence of stop lines for pedestrian or cyclist crossing zones, or in proximity of a traffic light. As we can see in Section 4.1 also this very important information is available now.
Regarding whether the extended HAD map information is accurate enough to effectively allow a computation of vehicle trajectory with satisfactory quality, the evaluation described in the following has been performed. The impact of the TomTom 3D lane model on the computed trajectory is measured in terms of how the resulting actual vehicle positions are close to the HAD map centre line points. In fact, having the vehicle well centred in the planned lane ensures a smooth and safe driving, as the system does not have to worry about- or react to threats that may occur out or the planned lane. As mentioned before, for the Hyundai AD system implementation, the trajectory planning considers the HAD map lane’s centre line as a reference for its planned trajectory calculation. If the centre line points are not sufficiently aligned over a straight path, or not monotonically shifted to a given direction along curves, then the vehicle computed trajectory can suffer oscillations with increasing extent as the misalignment increases. In extreme cases an oscillating trajectory can result in the vehicle having actual positions also oscillating and going out of the intended lane. In this context, taking a given HAD map stretch as object for evaluation, the following three steps are applied:

1. The HAD map lane centre line points’ misalignment is quantified
2. The planned vehicle trajectory are computed and actual vehicle positions measured
3. The distance offset between the actual vehicle positions and the planned lane centre line and boundary lines is also measured to finally verify if the vehicle is kept within the lane or not.

The above mentioned evaluation method is performed either in simulation or with the real AD vehicle achieving the same results. For the simulation, the HAD map is imported in the Gazebo simulation environment. The evaluation has been performed taking into account the TomTom HAD map for the Griesheim test track as well for the Braunschweig Tostmannplatz test site (see MAVEN deliverable D6.2 [36]), both including the MAVEN extensions as shown in Section 4.1. As it will be detailed in the following, for the Griesheim test track, a stretch including a challenging

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors’ view and the European Commission is not responsible for any use that may be made of the information it contains.

sharp curve towards the right is considered in order to prove the trajectory calculation reaction in worse case scenarios. For this stretch, all the three above mentioned evaluation steps are performed. As a result of the evaluation, it is concluded that the Griesheim HAD map 3D lane model data is very accurate and produces no relevant impact on the AD SW planned trajectory and actual vehicle position. For the evaluation of the Braunschweig Tostmannplatz HAD map 3D lane model, a stretch having the same length as the one for the Griesheim analysis is considered in order to have a suitable basis for comparison. For this stretch, only the first evaluation step is executed and its results compared with those of the Griesheim stretch. In fact, if the misalignment of the centreline points' of the Braunschweig stretch is quantified to be less than- or similar to that observed for the Griesheim stretch, it can be inferred with certainty that the computed trajectory for Braunschweig ensures the wanted quality requirements. This is even reinforced by the fact that the considered Griesheim stretch is much more challenging than any of the possible Braunschweig ones from a trajectory calculation point of view.

4.2.1 Griesheim HAD map evaluation

For this first HAD map evaluation, a stretch of approximately 400m is considered as highlighted by the two markers in the figure below.

Figure 48: Stretch considered for the Griesheim HAD map evaluation (visualized on GoogleMaps)

The HAD map lane centre line points' misalignment is quantified in terms of lateral offset between consecutive points. The lateral offset of a given point is defined as the orthogonal distance of the point from the segment passing through the two previous points (see in Figure 49, where this offset is represented on the x axis, where the y axis is on the segment of the previous points). In an ideal case, along a straight path consecutive points are perfectly aligned and the lateral offset is always null. Also, in an ideal case it is expected that over a curved path the misalignment is always in the same direction (e.g. for a curve to the right, every consecutive point has a positive offset compared to the previous two).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

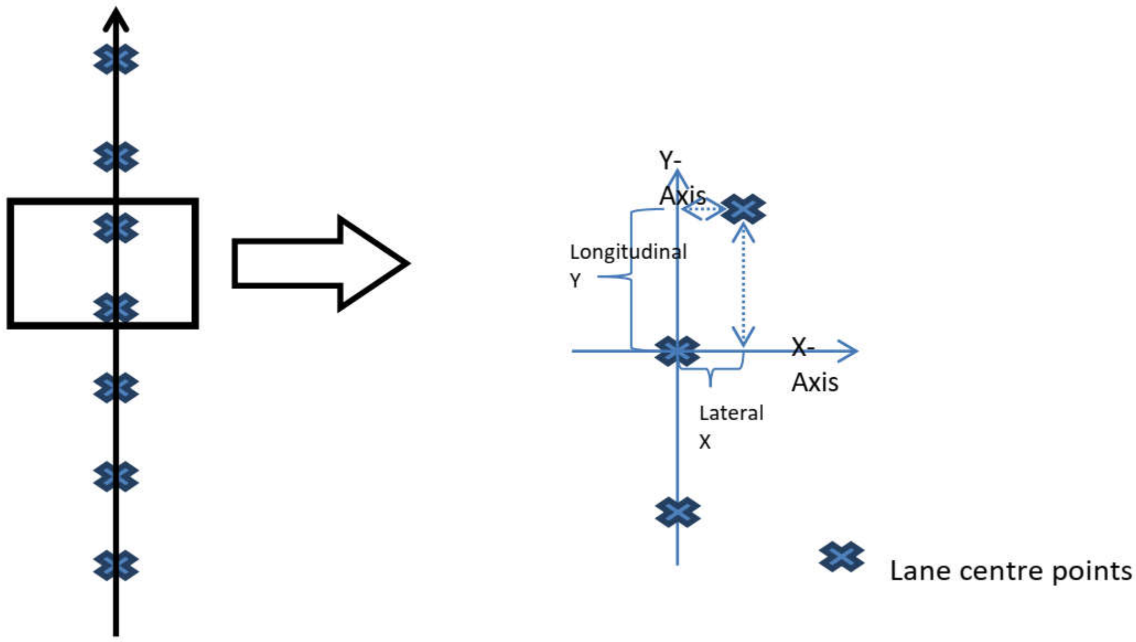

Figure 49: Definition of lateral offset

The next figure provides a graphical representation of the lateral offset for the HAD map lane centre points contained in the considered Griesheim stretch. The points considered for the calculation start from the right marker in Figure 48 and go towards the left marker, which implies that the right part of the graph in Figure 50 corresponds to the HAD map points of the curve.

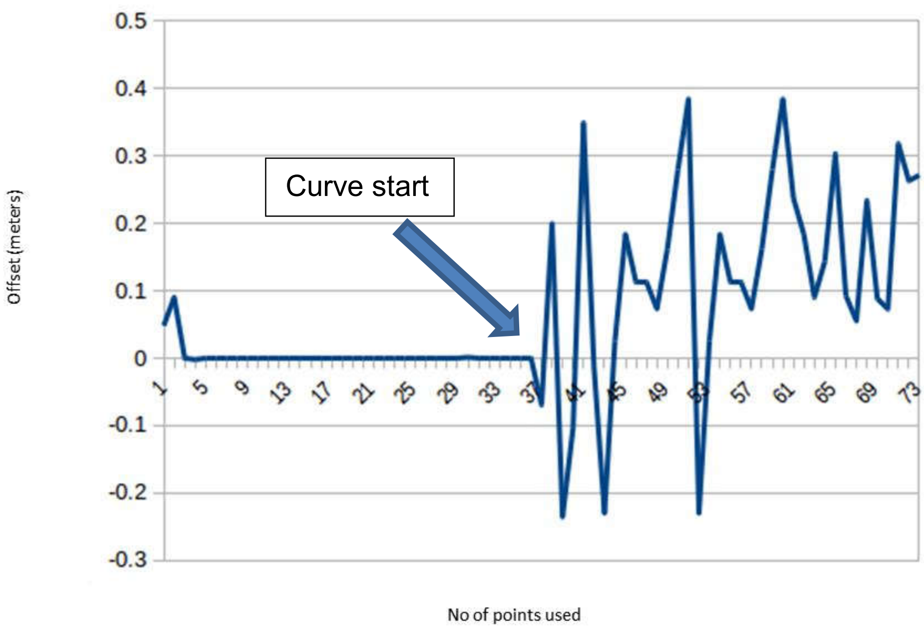

Figure 50: Centre line points' lateral offset on the Griesheim stretch

As it can be observed in Figure 50, the lateral offset, even if minimal, is not always null over straight path. Also, over the curved part of the stretch, offsets are not always in the same direction

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

as they assume both positive and negative values. The results of the lateral offset quantification are summarized in the next table.

Table 4: Quantification of centre line points' lateral offset on the Griesheim stretch (units in meters)

Description	Maximum Value	Minimum Value	Average value
Lateral offset in right direction	0.384047	2.39E-05 (~0)	0.06604278
Lateral offset in left direction	-0.23539	-2.19E-06 (~0)	-0.021816936

To assess the impact of this lateral offset values on the computed vehicle trajectory and actual positions, simulations and real drive tests have been performed. The next figures indicate graphs depicting the path followed by the AD vehicle compared with the HAD map 3D Lane model centre line points. The path is the set of consecutive vehicle positions. In the graphs, 3D lane model points for the right and left boundaries of the planned lane are also depicted. The y axis report distances in meters.

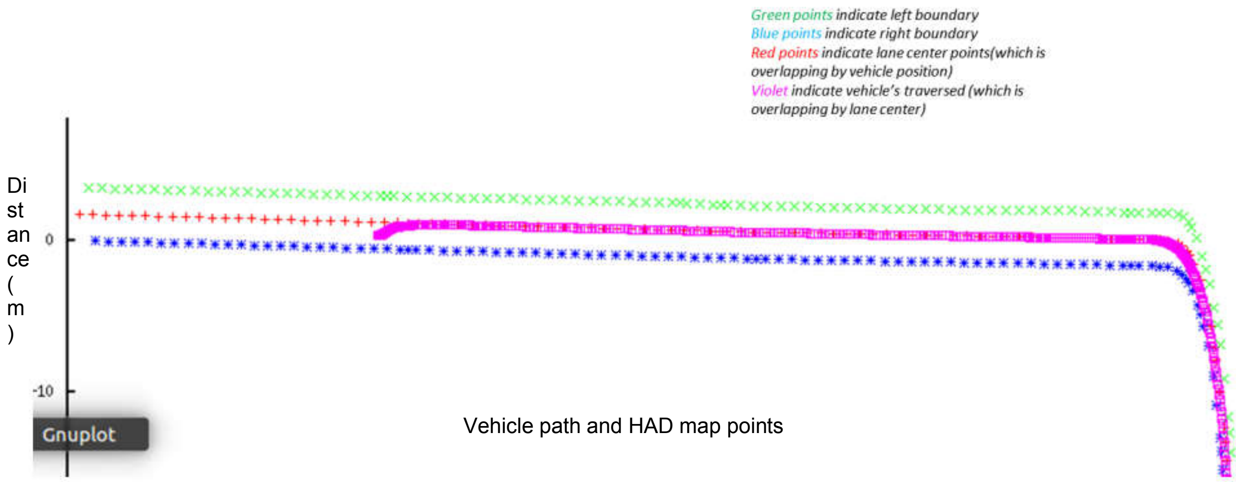

Figure 51: Vehicle path compared to 3D lane model on the Griesheim stretch

In the graph of Figure 51, 3D lane model points for the right and left boundaries of the planned lane are also depicted. This allows demonstrating that the vehicle traversed path is always within the lane boundaries.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

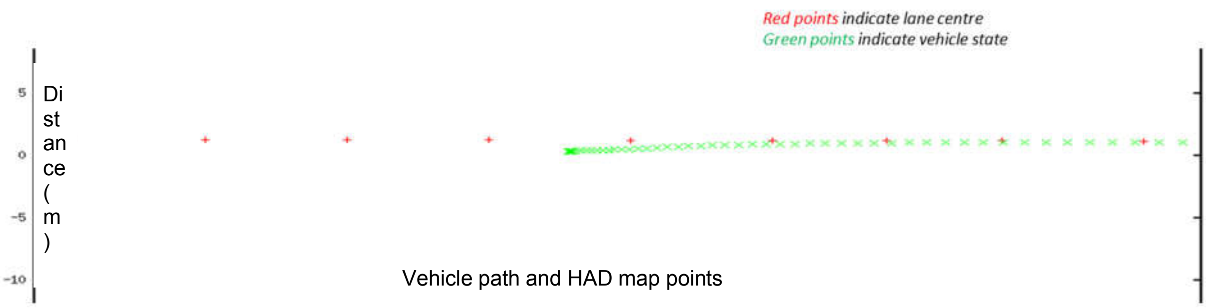

Figure 52: Vehicle path compared to 3D lane model on the Griesheim stretch (zoom 1)

Looking at the zoom of Figure 52, it is possible to see an initial offset of 0.3m between the vehicle position and the lane's centre line. This is simply due to the fact that the vehicle AD driving was started when the vehicle is not still occupying the centre lane position. As soon as the vehicle moves, it aligns with the centre line and the offset goes quickly to zero.

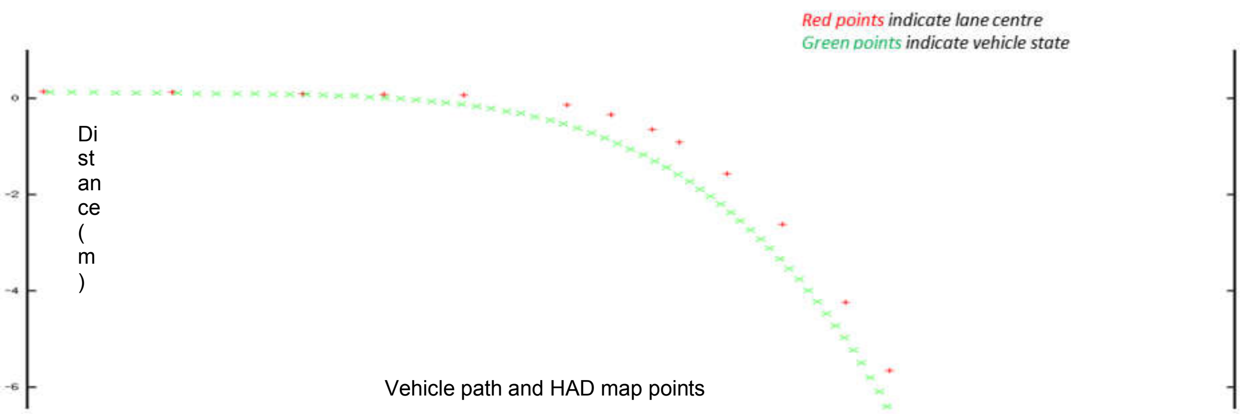

Figure 53: Vehicle path compared to 3D lane model on the Griesheim stretch (zoom 2)

On the contrary, the zoom of Figure 53 depicts the vehicle path when starting the curve. Here the vehicle is not able to perfectly maintain the centre of the lane (the curve is very tight) and an offset of up to 0.7m is observed between the vehicle position and the centre line.
As it can be seen from the above figures, the vehicle is moving almost always much aligned to the HAD map centre line of the planned lane, always being within the boundaries. To prove this conclusion with numerical results, the distance offsets between the actual vehicle positions and the planned lane centre line and boundary lines are also reported in graphs. The definition of these offsets is graphically represented in the next figure:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

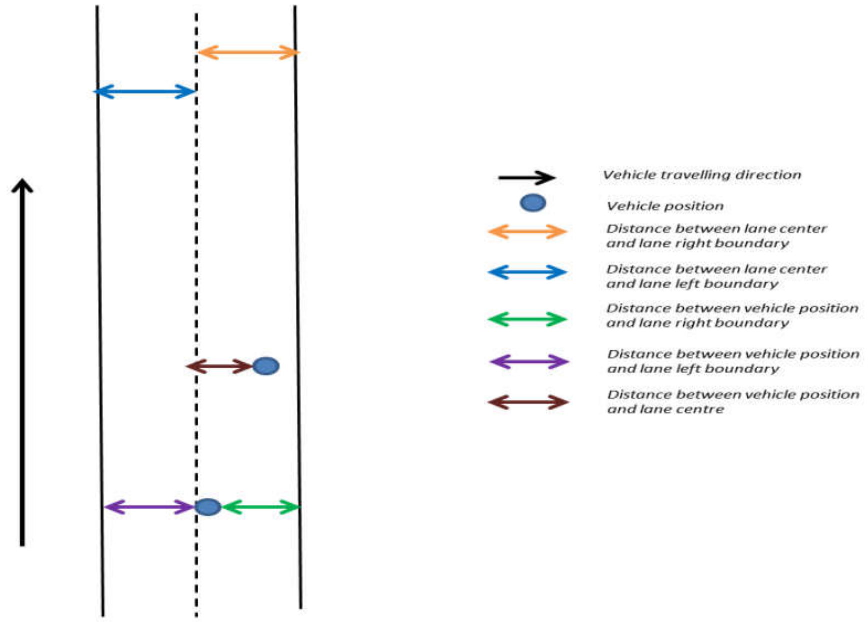

Figure 54: Graphical definition of offsets between vehicle positions and HAD map points

In Figure 54, the distances between the lane centre and boundaries are the optimal distances that the vehicle should ideally keep from the boundaries. They are computed using the lane width parameter provided in the HD map database, which is averaged for a particular lane in a given lane group. The next figure depicts the time evolution of the above defined offsets as the vehicle moves along the considered stretch.

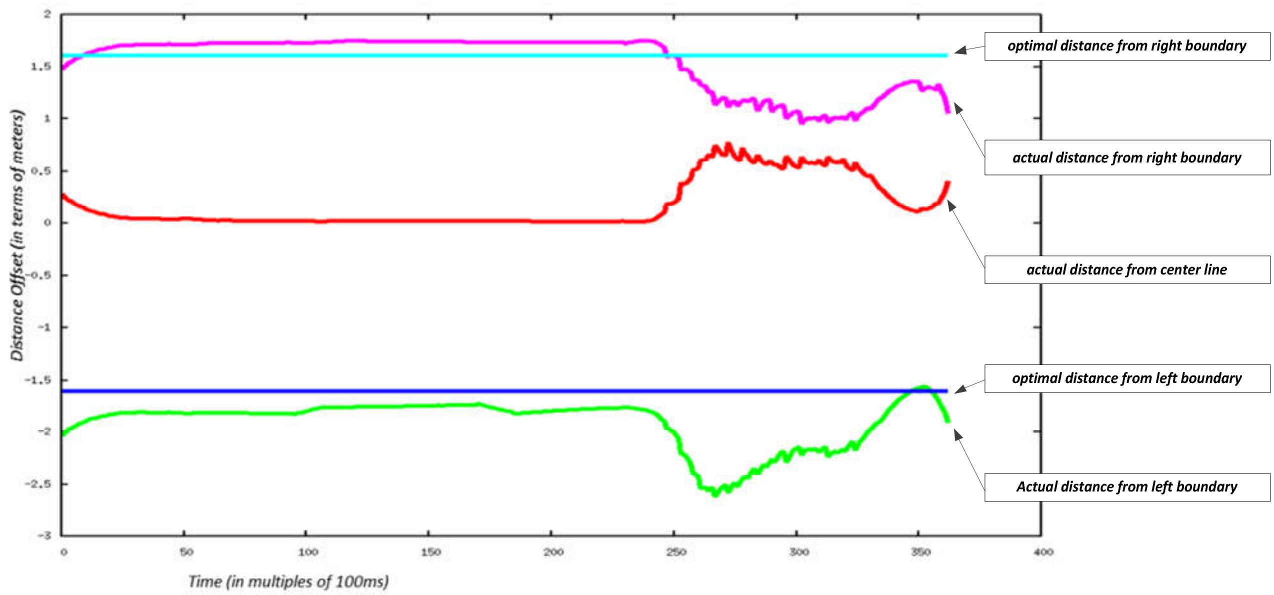

Figure 55: time variation of the offsets between vehicle positions and HAD map points on the Griesheim stretch

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

Initially, when still being on the straight path, the vehicle is aligned with the lane centre. When approaching the curve, the car cannot perfectly maintain this alignment and hence the offsets to the right and left boundaries start to deviate from the optimal values. Nevertheless, as demonstrated by the offset from the centre line, the car keeps staying within the lane. The fluctuation in actual distances observed is due to minute misalignment of centre line points. This causes minute vehicle deviation from the centre line which in turn creates misalignment with the measures with respect to the lane boundaries.
The results of this vehicle offset quantification are summarized in the next table.

Table 5: Quantification of the vehicle position offset on the Griesheim stretch (units in meters)

Description	Maximum distance offset maintained (in meters)	Minimum distance offset maintained (in meters)	Average distance offset maintained (in meters)	Optimum distance offset value to be maintained(in meters)
Left boundary distance offset from vehicle position	2.6209	1.55641	1.809344507	1.75086
Right boundary distance offset from vehicle position	1.78297	0.949066	1.671325806	1.75086
Lane centre distance offset from vehicle position	0.777034	0.000211255	0.069584125	0.0
Maximum distance offset seen	0.87004 (maximum value is coming from left boundary)			
Average distance offset seen	0.07964 (average value is coming from right boundary)			

This table provides maximum, minimum and average values of the distance offsets observed on the vehicle. Along with this, the optimum distance offsets to be maintained are also provided. By subtracting the maximum observed boundary distance offset from the optimal boundary distance offset, we obtain the maximum deviation observed from an optimal offset value that is 0.87m occurring for the left boundary. Nevertheless, if we subtract the average observed boundary distance offsets from the optimal boundary distance offset, we obtain an average deviation from an optimal value that is much less (0.07m, occurring for the right boundary). Moreover, the average observed distance from the centre line is also very low (0.069m). As demonstrated in Figure 55, these offsets do not cause the vehicle to leave the driven lane.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

4.2.2 Braunschweig HAD map evaluation

For the Braunschweig HAD map data set evaluation, a stretch of the same length as the Griesheim one is considered as highlighted by the two markers in the figure below.

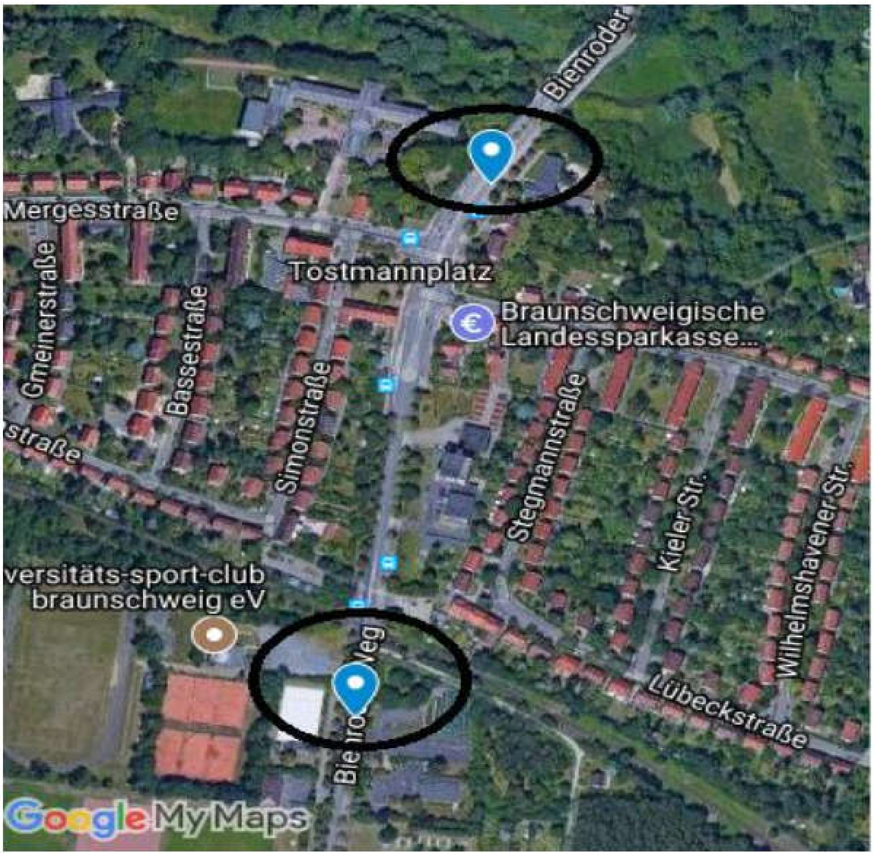

Figure 56: Stretch considered for the Braunschweig HAD map evaluation (visualized on GoogleMaps)

The next figure provides a graphical representation of the lateral offset for HAD map lane centre points contained in this stretch. The points considered for the calculation start from the lower marker and go towards the upper marker, which implies that the right part of the graph in Figure 50 corresponds to the HAD map points of the curves. For better understanding, in the figure the Braunschweig data is compared to the analogous Griesheim data (Figure 50). As it can be observed, the maximum lateral offset variations over the two stretches are in the same range of values. As the maximum lateral offset variations are those that most impact the quality of the computed vehicle trajectories and actual positions, it can be concluded that the trajectory that would be generated for the Braunschweig stretch would have a quality not lower than that verified on the Griesheim stretch.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

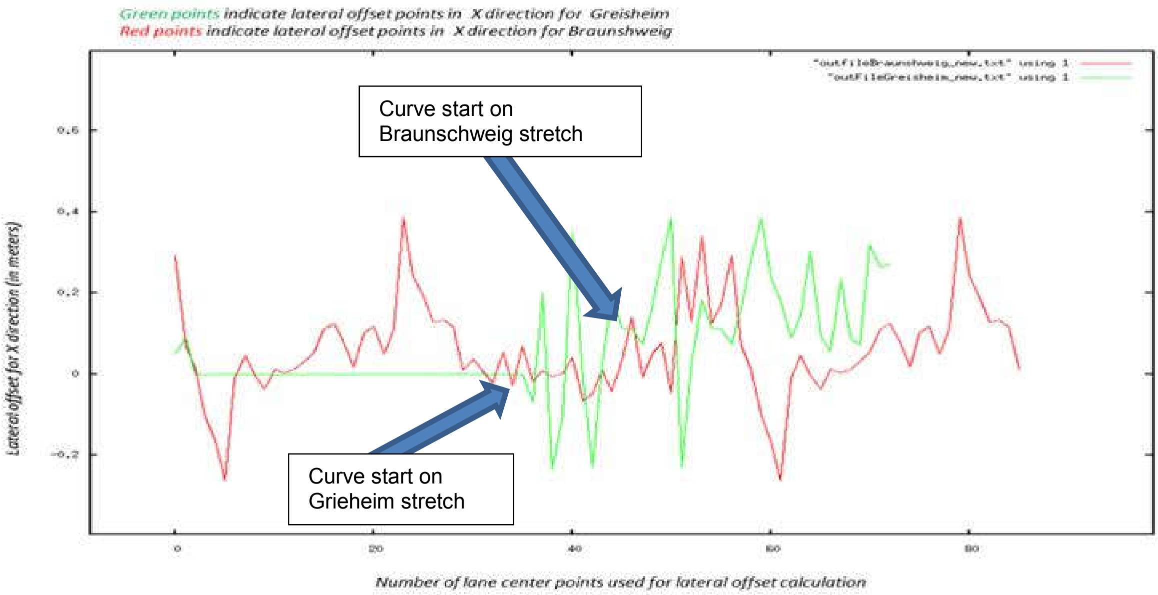

Figure 57: Centre line points' lateral offset on the Braunschweig stretch

Table 6: Quantification of centre line points' lateral offset: comparison between Braunschweig and Griesheim stretches

Description	Maximum Value (Braunschweig)	Maximum Value (Griesheim)	Minimum Value (Braunschweig)	Minimum Value (Griesheim)
Lateral offset in right direction	0.385299	0.384047	0.003037	2.39E-05 (~0)
Lateral offset in left direction	-0.26223	-0.23539	-0.00217	-2.19E-06 (~0)

4.2.3 Impact of extended HAD format in the AD motion profile

In the previous sections it has been highlighted that the MAVEN HAD map format has been extended with important information such, as stop line and crossing points, that is necessary for the AD vehicle to understand where to stop in case of conflicting situations (such as red phases at traffic lights, etc). To demonstrate the impact of this additional piece of information in the motion profiles of the AD vehicle, both simulations and drive tests taking into account the Griesheim HAD map have been performed. The AD system uses the distance from the stop line to generate a goal way point and associated speed such that the vehicle stops before the stop line point if needed. The stop line information has been embedded in the Griesheim HAD map following the same format as shown in Section 4.1. The exact position of the stop line is depicted by the left marker in the next figure. The right marker is where the vehicle starts moving automated.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

Figure 58: Embedded stop line position on the Griesheim track (visualized on GoogleMaps)

The next figure represents the desired velocity generated by the AD vehicle while approaching the stop line. For testing, the vehicle starts 73m before the stop line. The AD SW emulates a conflicting simulation at the stop line and triggers a deceleration 50m before the stop line for reaching a full stop when arriving there.

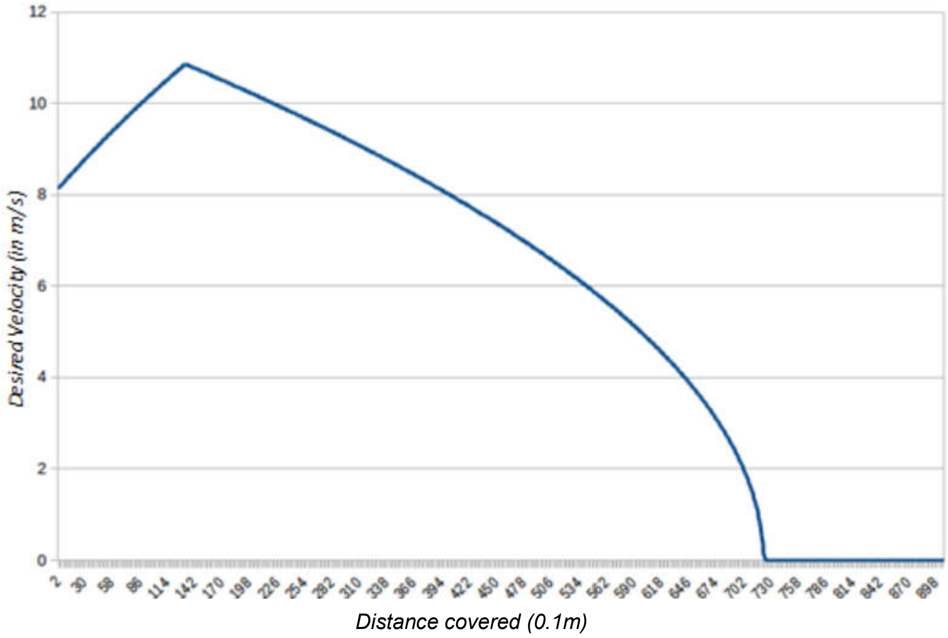

Figure 59: Motion profile of the AD vehicle before the stop line

On the contrary, the next figure depicts the desired velocity profile after the conflicting situation disappears and the vehicle can restart. The velocity ramps up and reaches the maximum allowed value of 50 kmph.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

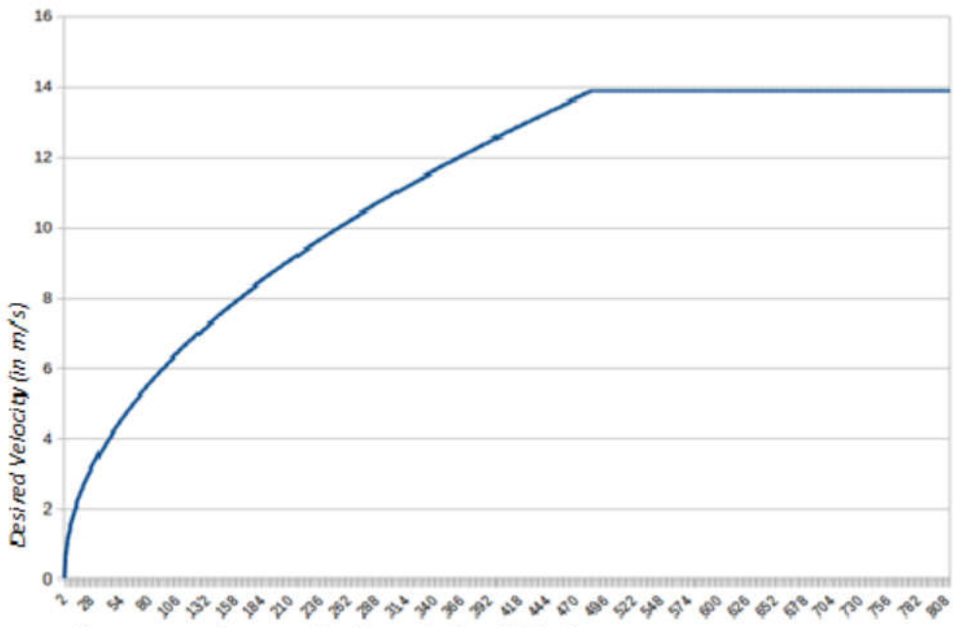

Figure 60: Motion profile of the AD vehicle after the stop line

4.3 DLR post-processing and conversion into OpenDRIVE®

As introduced in Section 2.3, the TomTom HAD map input data had to be converted into OpenDRIVE® [21]. This has been realised following the Road2Simulation guidelines [34], using an intermediated format based on OGS Simple Features [35]. The manual and visual element annotation was carried out in QGIS (see Figure 1), working directly on the Road2Simulation data model v1.2, which in turn was deployed in a PostGIS database as part of AIM Data Services [41], situated in the AIM Backend of DLR's Institute of Transportation Systems. Simple LineStrings [35] were created in this GIS environment with added tabular attributes, such as actual element types, element properties and reference links to other elements. Most of these attributes have been copied from the TomTom data directly and missing ones added accordingly to complete the Road2Simulation model specification.

During the project period of Road2Simulation the DLR developed a prototypic post-processing toolchain to export generalized Road2Simulation geodata into OpenDRIVE® as the internally used road description format for diving simulation and vehicle function development. This toolchain mainly supported simple urban and extra-urban settings but had to be extended and enhanced in order to process the TomTom HAD map data.

At the Tostmannplatz in Braunschweig the TomTom HD data contained completely modelled connections in the intersection area, i.e. including outer lane borders. The intersection itself only consisted of the axle from north to south which led to missing turn possibilities towards the western and eastern arms. At intersection areas on the air field in Griesheim only lane centre lines of connections were included in the TomTom data. The necessary outer lane borders were not modelled at all and had to be added manually to comply with the Road2Simulation and OpenDRIVE® representations.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

In general, following our simple modelling approach of roads in OpenDRIVE®, having each road's reference line in the centre of the road or at the outermost border, leads to sampling problems of lane geometries towards the centre of curvature in sharp curves. This results from the mathematical representation of lane geometries in OpenDRIVE® which are always relative to the road's reference line. It could be overcome by usage of so called "lane offsets" which were not yet implemented and not tested sufficiently.

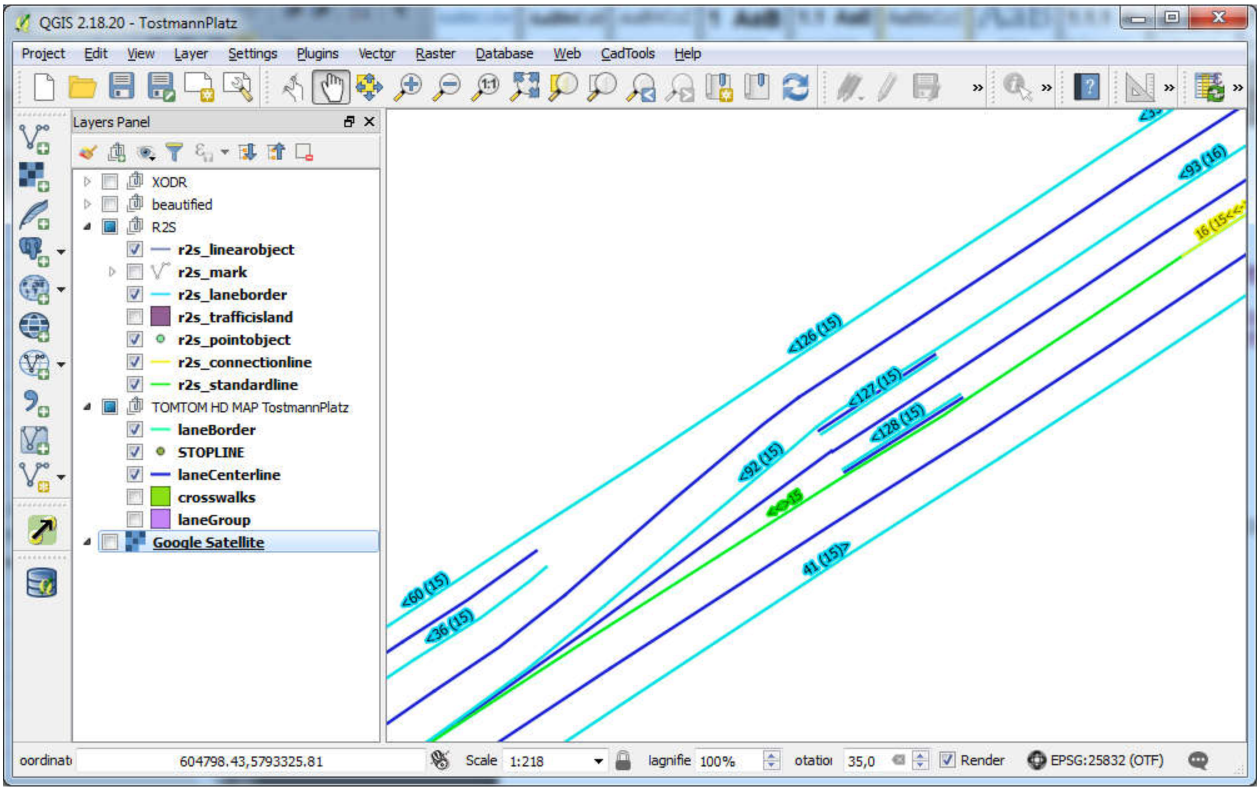

Figure 61: Exemplary annotation of Road2Simulation vector elements (green, yellow, cyan) based on TomTom HD map reference data (laneCentrelines are violet) in QGIS

The following Figure 62 shows a part of the Tostmannplatz map converted into OpenDRIVE® segments and read by the DLR vehicle automation software. In blue colour, a trace of standard GPS data combined with an inertial system is shown. Please note that the trace leaving the road to the left is the resulting trace for turning. The delivered TomTom map does not include this part of the map, as it has been agreed that all automated driving actions will not include turning on the Tostmannplatz. In addition it is important to mention that DLR is going to use differential GPS only when driving automated, as the lane matching needs to be enhanced.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

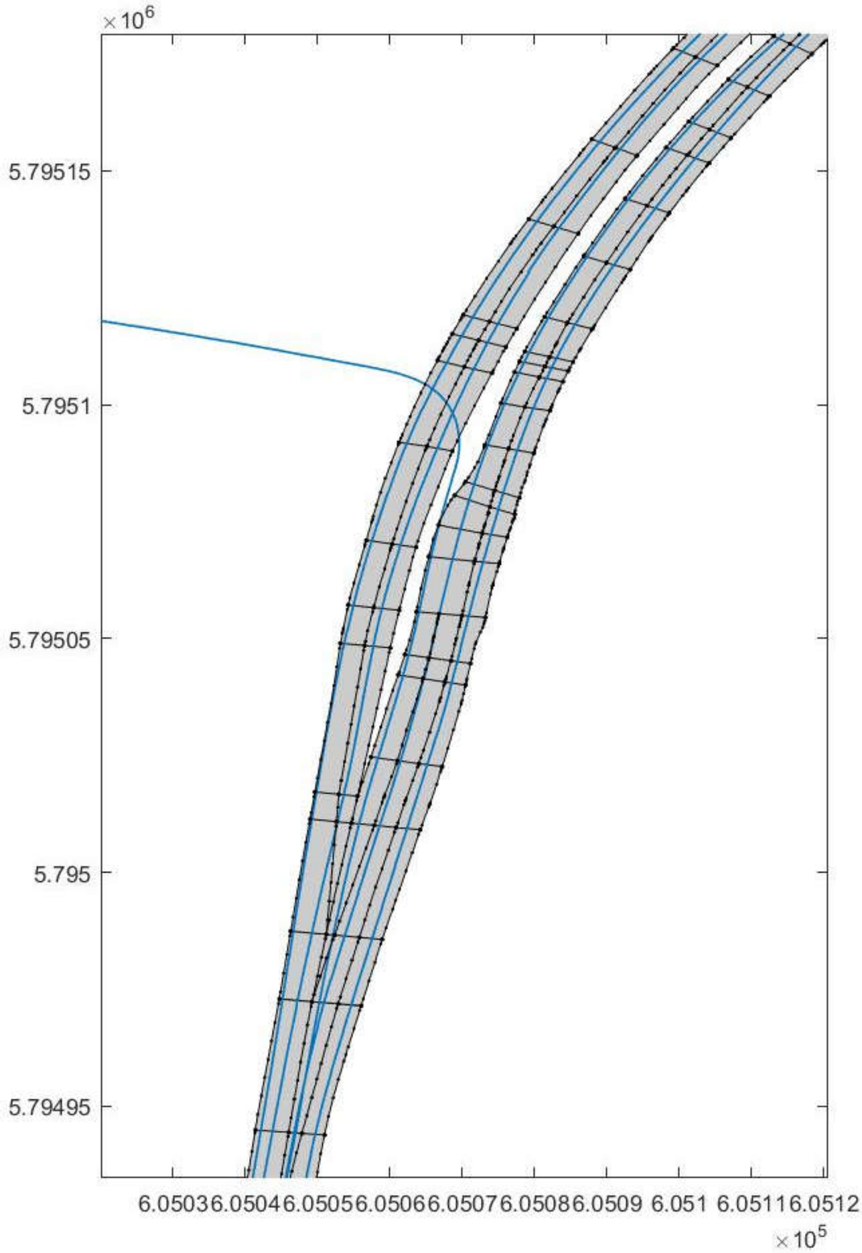

Figure 62: Standard GPS traces on the Tostmannplatz map converted to OpenDRIVE®

4.4 MAVEN HAD maps compared to standard definitions

To contextualize the MAVEN HAD map format and extensions with the definitions found in the SoA on HAD map standardization activities (Section 2.3.1.2), we have performed a comparison between the TomTom HAD map and a map according to GDF 5.1 specification (extension of [15]) that covers most features related to automated driving.

4.4.1 TomTom HAD maps

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

HAD map for autonomous driving provides driving lane-specific vectors and features in contrast to navigation maps that normally include just one vector per road belt. It allows for a vehicle and obstacle localization within the driving lane, laterally and longitudinally. The format relies on the concept of lane groups, which contains lane centre lines. Every lane centre line can have multiple boundaries on left and right side. The format also uses way points to express features along the centre lines (lanes) and global lane group objects to express features with separate geometry associated to the lane group itself.
Lanes are grouped to lane groups, lane groups are based on similarities of grouped lane features, whenever there is a change of selected parameters a new lane group adjacent to the previous group is formed. Lane groups can be seen on the next figure as polygons formed by grouped lane boundaries.

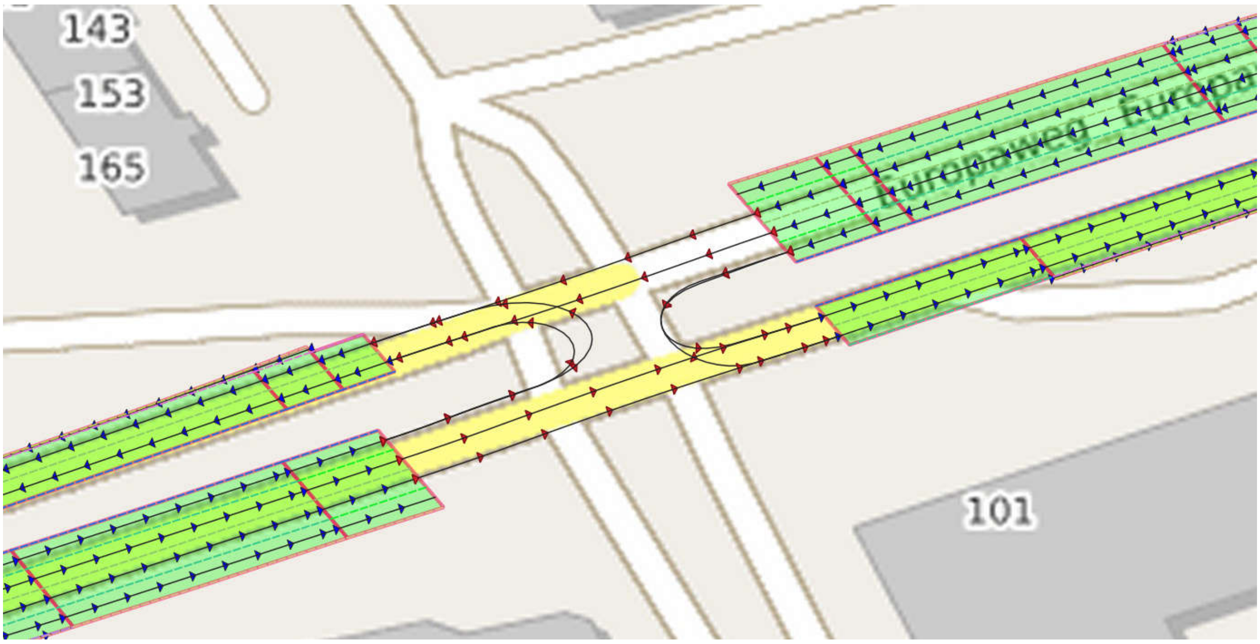

Figure 63: HAD map sample with lane groups, lane boundaries, centres and connection lines (possible trajectories) at intersections

HAD map features are as follows:

- Geometry
    - Centre lane geometry for each lane.
    - Multiple lane border geometry for each lane (at least 2, but can be more).
    - Topological connection of adjacent centrelines and complex geometry connection of centre lines of ingressing and egressing lanes.
    - lane group objects (traffic signal, stop line, crosswalk, …) can be referenced to centreline
- Attributes
    - lane types (split, merge, …)
    - lane boundary types / separators (curb, dashed line, …)
    - link to navigation map vectors
    - link to RoadDNA [42] map feature (for precise positioning)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

the TomTom HAD map is set up with simplicity, having only road belt lanes identified and described. Its main advantage is in precision and localization, achieved thanks to the RoadDNA feature that could be used for sub lane level positioning in in-vehicle local dynamic map (see Section 5.1).

4.4.2 GDF 5.1 maps with road belt concept

The focus of the ISO GDF 5.1 standard is on emerging ITS applications and services, such as C-ITS and automated driving. It emphasizes road, lane and relevant information on road and lane. In GDF5.0 basic data model [15] describes road and road related objects, where lines and points express roads and intersections. C-ITS and automated driving systems, however require highly defined information that enables a vehicle to identify where it is driving in a lane, and to identify which lane of a road it is in. To acquire such information, GDF 5.1 allows roads and road related objects (e.g. lane) to be expressed as a specific area feature that may be converted into a line shape to represent a general direction of vehicular movement, such as a reference line or centre line of lane and/or a usual vehicle trajectory in a lane. This area feature is referred to as a "Belt", it is bounded by side lines and terminal lines. This specification is aligned with, ISO 14296:2016 [18]

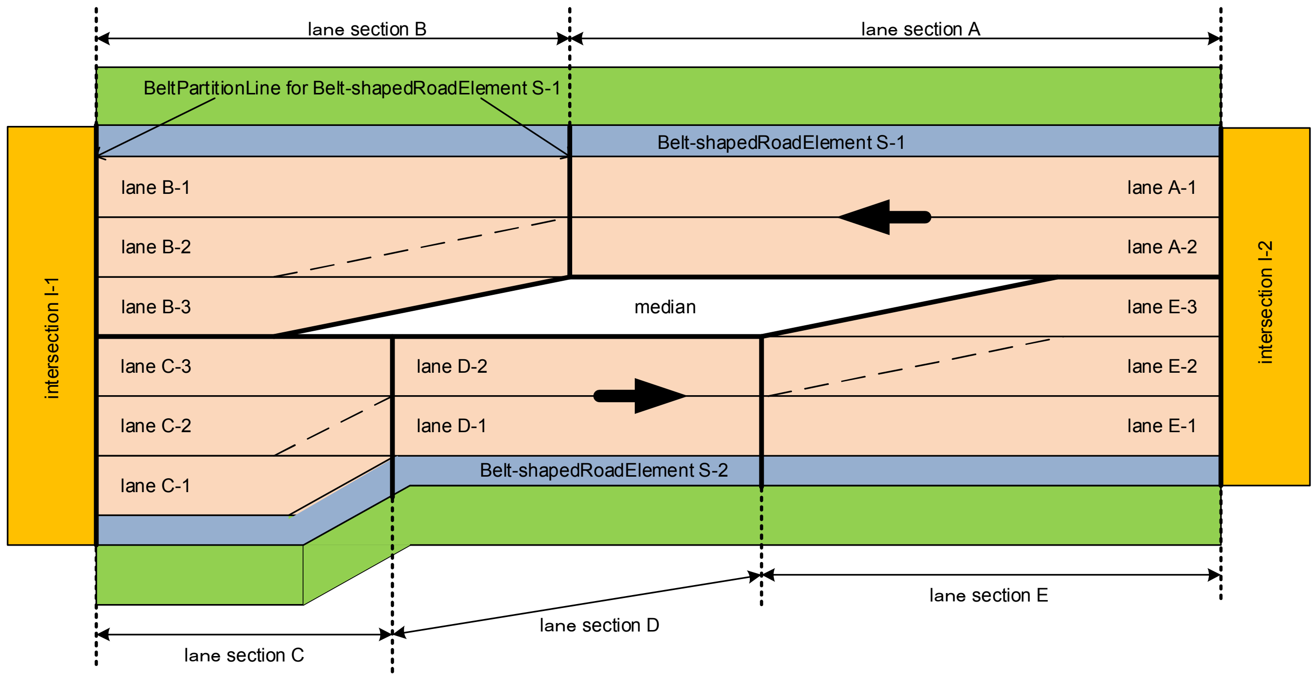

Figure 64: Belt representative features, lane sections divided by partition lines (dashed) [ISO 14825]

The Belt concept allows for several levels of abstraction RoadBelt > Belt-shapedRoadElements > LaneBeltElement, each having its own features (centrelines, connection points, border and terminal lines) that might or not be shared with lower levels. Some levels of abstraction may be skipped. RoadBelt represents an area of the road that includes carriageways, median (island) sidewalks and safe space for evasive manoeuvres to avoid traffic incidents. Sidelines of a RoadBelt are defined by boundary lines such as outlines of road furniture (i.e. side ditches, walls and fences including green estate in that boundary) that border road side objects (i.e. town areas, buildings, parks and rivers) along the road. Terminal lines of RoadBelt are virtually defined. At each

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

terminal line, RoadBelt is always connected with IntersectionBelt. An IntersectionBelt connects to RoadBelt and/or Belt-shapedRoadElements. Side lines of IntersectionBelt are defined by boundary lines such as corners of the intersection and outlines of the public square.

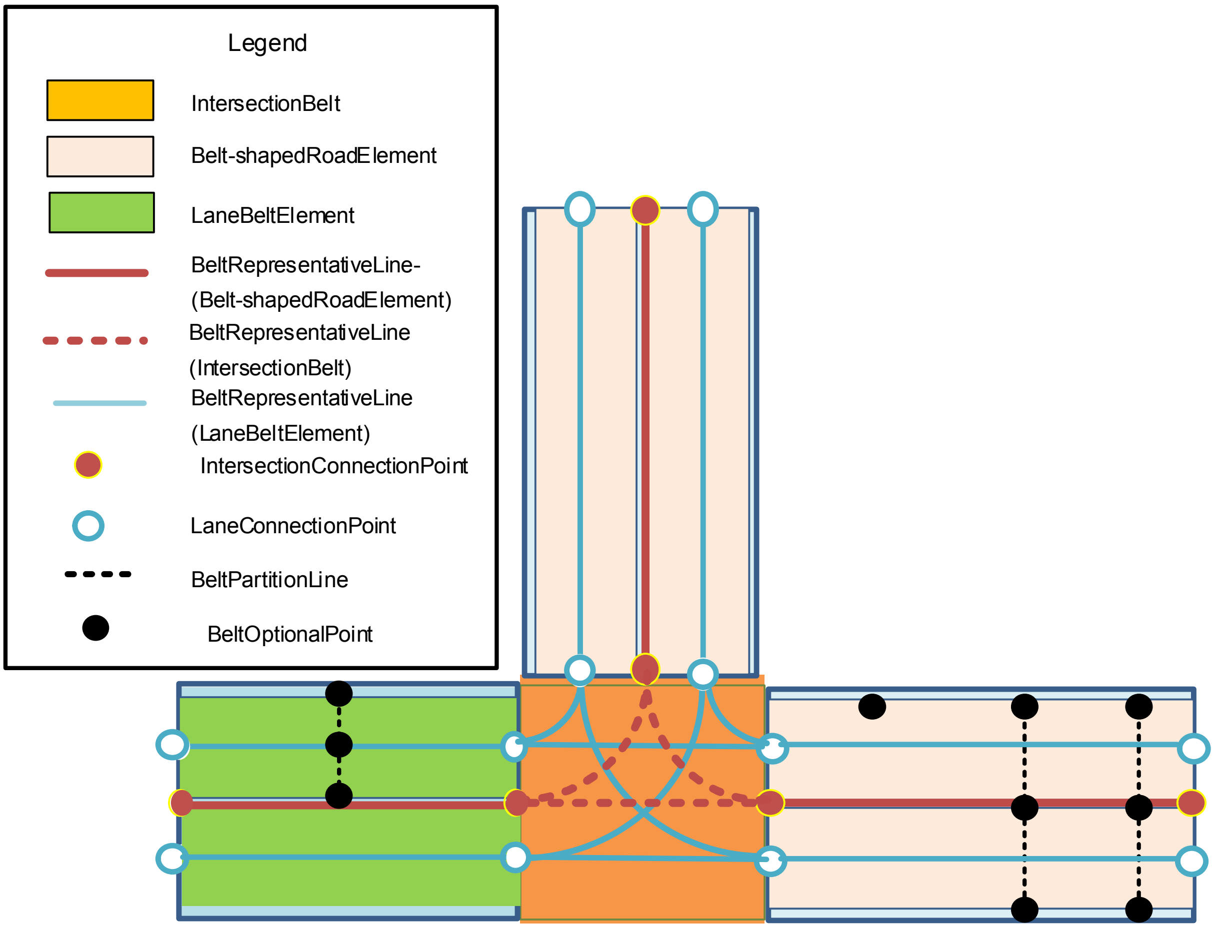

Figure 65: Belt representative features [ISO 14825]

Lanes can be grouped into lane sections (Belt-shapedRoadElements) divided by BeltPartitionLine. A boundary of a lane section is set at the location where important characteristics of the carriageway regarding lanes vary (i.e. lane-diverging, lane-merging, increasing number of lanes, decreasing number of lanes, narrowing or widening width with same number of lanes etc.). LaneBeltElement expresses an independent lane area where the vehicles are to stay between a couple of the lane boundaries or markings, and serves as the smallest unit of space for vehicles cruising. At each terminal line of LaneBeltElements are connected by LaneBeltJoints. A BeltRepresentativeLine is a Line Feature expressing a path connecting between a pair of terminal lines of RoadBelt, Belt-shapedRoadElement, LaneBeltElement or IntersectionBelt. BeltOptionalPoint on the side-line of Belt feature provides the contact points and a contact extent of features (e.g. Road Furniture). BeltPartitionLine may be set on the location of Road Marking (i.e. pedestrian crossing and stop line) or Road Furniture (e.g. pedestrian overpass) or Structure (e.g. railroad crossing, bridge and tunnel). Regarding carriageways and lanes, applications for ADS and C-ITS require both “belt-shaped data model” and conventional “link & node data model”. GDF 5.1 part 1 provides Road Element and Junction as the conventional “link & node data model”. BeltRepresentativeLine has attributes for specifying the related Belt Feature.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors’ view and the European Commission is not responsible for any use that may be made of the information it contains.

BeltRepresentativeLine (for both Belt-shapedRoadElement and IntersectionBelt) and IntersectionConnectionPoint may form a linear road network. BeltRepresentativeLine of LaneBeltElement and LaneConnectionPoint may form a linear lane network as well.
To summarize, this list of features allows defining road surface area down to the level of individual lanes. Grouping of area segments is based on same features of lower level areas. Terminal lines that are shared hierarchically with all areas terminate areas. Side lines allow for detailed definition of a border type. Centre lines based on the area level and type of the line could represent the centre of the lane, road, or recommended trajectory of a vehicle. Centre lines are connected via “connection points” to create a routable network.

4.4.3 Conclusions on two reviewed models

Only two models were reviewed in previous section: TomTom HD map and GDF 5.1 with belt concept. Generally, the models allow for the same basic functionality:

- Driveable and non-driveable road surface represented as a polygon.
- Specification of area border type.
- Specification of a “routable” centre line through lanes and intersection.
- Road objects could be easily attached to centre lines.

These differences that may not have significant impact on the practical use were identified:

- TomTom HAD map allows for greater simplicity and, through direct transformation to NDS format, easier and quicker implementation.
- GDF 5.1 areas have greater versatility due to introduced hierarchy, from which other features could benefit, such as:
    - GDF 5.1 comprises both navigation and HAD map view in one model specifying centre lines for belts and for lanes. The former could be used as navigation road network, while the latter as the lane level network. TomTom HAD map specifies link to navigation map, whereas the navigation map has to be maintained and stored separately.
    - GDF 5.1 defines intersection areas complete with borders.
    - GFD 5.1 defines safe space for evasive manoeuvres as a part of the belt concept.

One difference that have a significant impact on practical use have been identified, it is the RoadDNA feature allowing more precise localization of the vehicle on the road network.

4.4.3.1 Notes concerning the corridor approach – MAVEN extension

The corridor approach is a pair of virtual boundary lines, defining the space for manoeuvre through the intersection. The boundary lines do not reflect real lane markings (at intersections lane markings are generally not present) but connects the boundary lane markings of inbound lanes to boundary lane markings of outbound lanes. The corridor should match the reality to make sure that they do not include obstacle such as "intersection islands". The corridor approach as proposed by MAVEN (here, within this document) is not being supported by any of the reviewed map concepts, since it does not reflect reality of the road, as such it can be artificially reconstructed from intersection lines. As a consequence, the MAVEN corridor approach could be proposed for standardization.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

5 Lessons learned

In this Chapter, lessons learned relevant to the objectives of the deliverable are presented. These lessons have been learned by the involved partners before and while implementing, testing and evaluating the functions described in the previous sections.

5.1 RoadDNA – Localisation improvement technologies using landmarks

As part of the MAVEN project investigations on affordable sensor setups, HMETC used the new vehicle positioning aiding technology from TomTom called RoadDNA. TomTom RoadDNA consists of a localization layer on top of the HAD-map. When using a LIDAR the TomTom RoadDNA Roadside layer is recommended. This localization layer is built by converting a 3D point cloud of roadside patterns into a compressed, 2D view of the roadway representing each side of the road (see Figure 66). The Roadside layer contains depth information of objects placed on both street sites (e.g. road barriers, buildings, traffic signs, trees). A traveling vehicle will try to correlate the RoadDNA data (as provided by the RoadDNA Roadside HAD Map layer) with the data collected by its own sensors (e.g. front LiDAR, roof mounted 360° LiDAR, IMU, GNSS [GPS, GLONASS and/or Galileo,] etc.) to accurately locate itself in the TomTom HAD Map. For RoadDNA Roadside to work optimal, stable sensor data which reflects the surrounding environment (LiDAR point cloud with a good wide field of view), a GNSS position and vehicle acceleration/deceleration/yaw values (for example generated by an IMU) are required. The target accuracy with high precision sensors in optimal conditions (e.g. good quality of the vehicle sensors and positioning source with no surrounding traffic) are <15cm lateral and <50cm longitudinal relative accuracy [42]. Using RoadDNA Roadside in combination with series GNSS devices would permit avoiding the costs of installing more the expensive DGPS systems and will enhance the position in case of poor or even no GPS reception (e.g. between high buildings or in tunnels).

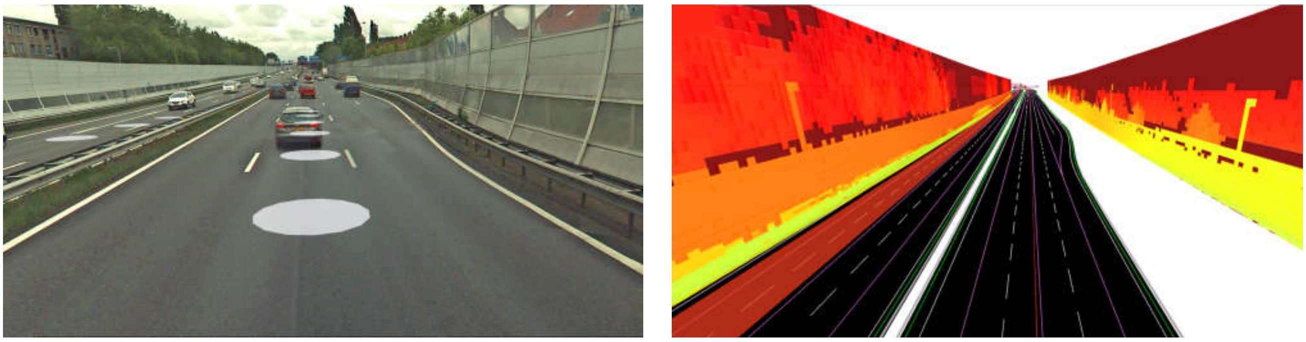

Figure 66: Real road segment and TomTom RoadDNA representation [42]

5.1.1 RoadDNA tested scenarios and locations

The evaluation of the RoadDNA Roadside data was carried out on different MAVEN test sites (Helmond, Netherlands, Griesheim test track, Germany) as well as on other public road segments inside or nearby the HMETC facilities in Ruesselsheim, Germany (see next figures). HMETC used TomTom HAD maps and corresponding RoadDNA Roadside data which was created during the project (most current version used and tested).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

To be able to make use of the RoadDNA Roadside data without investing additional time and effort in implementing a correlation library, HMETC has used the TomTom RoadDNA Roadside reference implementation. This is also known as the RoadDNA Correlator library. It should be noted that the TomTom RoadDNA Roadside reference implementation is solely intended to proof that RoadDNA Roadside data can be used for localization; the reference implementation is not intended to be used for in-vehicle localization as is because of its known limitations in covering all corner cases. Known limitations of the reference implementation are insufficient localisation accuracy in curves, sharp turns and places with segmented reference lines in the content (e.g. as is the case for crossings and T-junctions); evaluating the content (RoadDNA roadside) in those areas whilst using the TomTom reference implementation will not produce satisfying localisation results. This is because of known limitations of the reference implementation and not because of errors in the content.

Figure 67: Darmstadt - Griesheim "August-Euler-Flugplatz" test track, Germany (visualized on GoogleMaps)

Figure 68: Helmond test intersection, The Netherlands (visualized on GoogleMaps)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

Figure 69 HMETC facilities & public roads, Germany (visualized on GoogleMaps)

An OXTS RT3003 DGPS system (with a cellular network based RTK service) with centimetre-level position accuracy was used as reference system to compare with the RoadDNA Roadside correlated position results. In this context, it is important to be aware that RoadDNA Roadside provides as output the corrected vehicle position with respect to the corresponding TomTom HAD map. Although this HAD map has a centimetre-level relative accuracy, the absolute accuracy might be off by a maximum of 1 meter[2]. As a result, the DGPS values cannot be compared one-on-one with the RoadDNA corrected results as both techniques use a different reference. However, when taking into account the above, comparing both would still provide an useful reference indication of where the vehicle is driving in the reality. Both live data and pre-recorded data from the vehicle sensors (i.e. front and rear LiDARs, see Figure 10) and the supported GNSS source and IMU modules were fed into the RoadDNA Roadside library for processing. As GNSS source to the RoadDNA library, investigations with both the Oxford DGPS and a normal GPS (an automotive grade u-blox EVK M8L with Racelogic IMU) were conducted. The vehicle was traveling along the roads which were covered by the TomTom HAD Map including the RoadDNA Roadside data. The RoadDNA correlator was continuously run and results (i.e. computed positions) were recorded for offline analysis. Offline analysis results were continuously double checked with TomTom experts who provided a remarkable support in understanding the obtained values and suggesting suitable measures to improve them.

5.1.2 RoadDNA results and lessons learned

To check the basic functionality of RoadDNA Roadside the investigations were started by sourcing the library with the DGPS. This allows filtering out possible inaccuracies attributable to applying the normal GPS. With this test vehicle setup and in the given locations, RoadDNA was able to achieve the same accuracy as the DGPS along straight stretches as demonstrated in the next Figure 70.

[2] In fact, for an AD system, it is much more important to have HAD map points with high relative position accuracy than absolute position accuracy.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

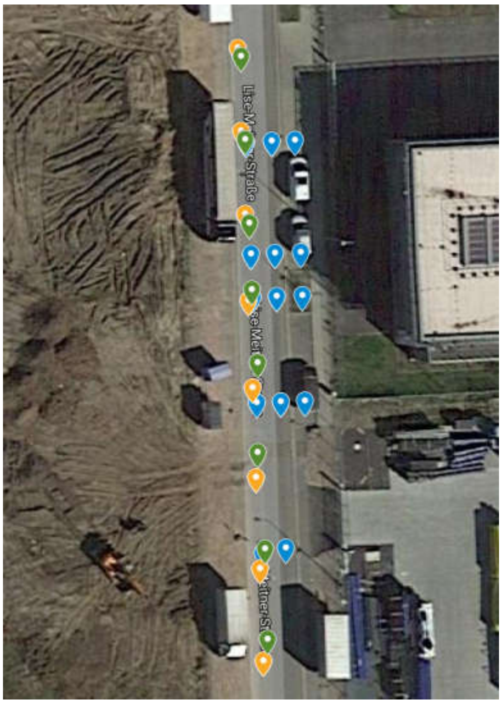

Figure 70: RoadDNA analysis on straight stretches using DGPS as source: Blue = HAD map lane centre points, Green = RoadDNA outputs, Yellow = DGPS samples (visualized on GoogleMaps)

As was stated earlier in the known limitations, it was indeed observed that the system could not provide precise positioning outputs right after curves (also slight curves, see Figure 71) as it needs some time to recover a high correlation between the real-time LiDAR inputs and the 2D images of the road edges in the RoadDNA database (known behaviour of the system). This was the first lesson learned from this analysis: in order to correctly applying RoadDNA Roadside data, independently on the applied GNSS source, the reference application needs to be replaced by a HMETC variant or the AD system needs to be equipped with some on-line filtering or camera-based recognition correction method to mitigate the inaccuracy of the RoadDNA Correlation library outputs right after curves.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

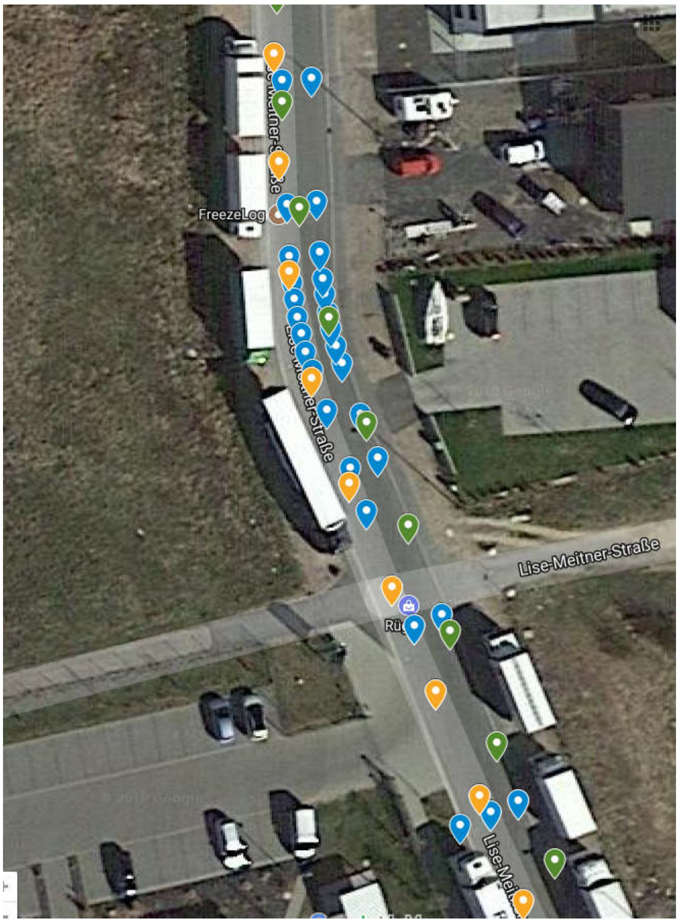

Figure 71: RoadDNA analysis on curved stretches using DGPS as source: Blue = HAD map lane centre points, Green = RoadDNA outputs, Yellow = DGPS samples (visualized on GoogleMaps)

Further tests were conducted using the normal GPS module as input to the RoadDNA library. Figure 72 shows the results of using the RoadDNA Roadside data in the Helmond test site. As it can be seen, over the straight stretch, the u-Blox GPS sample points are corrected by the RoadDNA Roadside and are placed right in the middle of the driven lane. In this case, the functionality generates longitudinal offset errors that can be attributable to high data load (i.e. density of LiDAR point clouds) or the lack of sufficient landmarks (e.g. buildings, signposts, trees, etc.) for proper longitudinal correlation. Further investigations would be needed to verify whether this is indeed caused by performance issues or lack of landmarks. Also, it needs to be investigated if a lower amount of point clouds would improve the performance without negatively affecting the positioning performance.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

Figure 72: RoadDNA analysis in the Helmond test site using normal GPS source: Purple = RoadDNA outputs, Blue = GPS samples (visualized on GoogleMaps)

As expected, RoadDNA Roadside was not particularly helpful on road segments without sufficient physical landmarks on the road edges (for example this was observed on the Griesheim airfield, having free space [e.g. no landmarks] at both road sides). This is due to the RoadDNA Roadside design that requires physical landmarks on the ground (trees, buildings, urban structures) for correlation. Moreover, the tested RoadDNA layer (Roadside) does not take any road surface changes into account, so it could not be particularly helpful in congested areas where the road edges were blocked by other vehicles[3]. For this it needs to be further investigated whether other RoadDNA layers (for example RoadDNA markings) can be used in addition.
As also highlighted in Section 3.1, HMETC focused on a more cost effective and reusable sensor setup solution which could be applied to future series production AD vehicle platforms. At this moment very precise positioning (lane level) with RoadDNA Roadside whilst making use of the existing RoadDNA reference implementation is only possible for stretches that do not contain sharp turns or crossings. This is mainly due to the known limitations of the reference implementation. Therefore for now complementing the Hyundai AD vehicle sensors setup with RoadDNA Roadside instead of relying on DGPS was not possible in any of the tested situations. As mentioned before, many test iterations with valuable support from TomTom experts indicated this to be caused by the following main reasons:

1) Known limitations in the RoadDNA reference implementation
2) Too noisy input signals (e.g. from IMU) which did not meet the minimal RoadDNA requirements
3) Suboptimal positioning of the LiDAR limiting the field of view and therefore not meeting the minimal RoadDNA input requirements (in terms of ability to detect objects at distance)[4]

These aspects will be further investigated in the future and already provide very good lesson learned for future exploitation of interesting solutions like RoadDNA. In fact, improving localization

[3] In this regard, it is important to say that the RoadDNA product family is going to be improved with a layer that takes into account road reflectivity and could be particularly helpful in these situations, but this version was not yet available for the HMETC evaluations.

[4] Actually, this configuration is not only adopted by the Hyundai AD vehicle, but it is already present in more than one series production cars sold by other automakers (e.g. Audi A8, 2018 model).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

precision by adopting DGPS and IMU sensor or using RoadDNA Roadside in combination with higher position-mounted LiDAR sensors (e.g. 360° LiDAR roof mounted) are not foreseeable at the moment as viable solutions for series adoption. The overall AD system accuracy and stability (especially relevant for turns at junctions or in obstructed areas) can be further improved by taking other sensors' recognition in combination with the corresponding RoadDNA HAD Map layers into account at AD prototypes (i.e. camera: lane markings + RoadDNA Markings, traffic sign post + RoadDNA poles and HD Map including sign posts, radar: road surface, buildings + RoadDNA Radar). As this might also lead to a higher processing demand, it was identified that processing latencies of the system could be reduced by high performance ECUs.
For all the above mentioned reasons, a DGPS was applied as positioning source for the vehicle control software in the experiments presented in Section 3.1. Further investigations will be made on the Hyundai AD vehicle setup to complement the RoadDNA performance with V2X receptions from RSUs to improve vehicle localization, which are out of scope for this document.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

6 Conclusion

This deliverable has described the project developments in terms of functions for protection of Vulnerable Road Users (VRUs) and CAVs' drivers as well as for Highly Automated Driving (HAD) maps.
As explained throughout the document, the functions for protections of VRUs and CAVs' drivers are considered in the context of MAVEN as seamless integration of ADAS functions into CAVs systems as well as extension of cooperative infrastructure algorithms to detect possibly dangerous situations and directly or indirectly influence CAVs automated reactions. In this context, two main classes of functions have been considered:

- Individual vehicle sensors data-assisted ADAS, and
- Cooperative sensor data-assisted ADAS

The main results achieved are summarized as follows:

- For individual vehicle sensors data-assisted ADAS the following functions have been developed:
  - A functionality for safe consideration of VRUs and obstacles seamlessly integrated in the MAVEN AD vehicle SW architecture, with application for automated detection and reaction when turning at road intersections. This functionality performs a threat assessment cosidering objects detected and tracked by the sensor fusion and crossed with information about drivable lanes and planned route outputs. In parallel, it calculates a feasible manoeuvre and accordingly plans a vehicle reaction in terms of lane change, deceleration or braking. The functionality has been tested in a controlled environment and has provided good results as long as the situation is not particularly challenging for the adopted vehicle sensor setup (VRU placed right after the vehicle turning point). Challenging situations like this opens possibilities for countermeasures via cooperative sensing approaches.
  - A functionality, seamlessly integrated in the MAVEN AD vehicles' SW architecture, for safe handling of situations in which a non-cooperative manually driven vehicle tries to interfere in a platoon of MAVEN cooperative automated vehicles. This functionality estimates other vehicles' intention to change lane by recognizing the indicator light setting with artificial intelligence methods, or by a road topology with merging lanes. After this detection is done, the reaction part is handled by the platoon logic embedded in the AD vehicle control SW, which control the safe distance at which a platoon vehicle follows its preceding vehicle. Evaluation of this functionality is going to be performed in future integration sprints (as planned by WP6), and hence the evaluation results are not reported in this deliverable (they will be reported in D7.2).

- For cooperative sensor data-assisted ADAS the following functions have been developed:
  - An improved functionality for safe consideration of VRUs and obstacles seamlessly integrated in the MAVEN AD vehicle SW architecture, with application for automated detection and reaction when turning at road intersections based on V2V CPM receptions. This functionality extends the corresponding approach based only on individual vehicle sensors to improve its performance. The developed logic includes information received in other vehicles' CPM messages to extend the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

environmental awareness beyond the capabilities of the ego-sensors and perform more conservative threat assessments. As demonstrated via tests executed in a controlled environment, the developed functionality drives timely vehicles reactions (deceleration and braking) to prevent collision risks with VRUs at intersections, overcoming the limitations of non-cooperative approaches.

- A functionality for safe consideration of VRUs and obstacles seamlessly embedded in the MAVEN vehicle AD SW architecture, with application for automated detection and reaction at road intersections based on CPM receptions form the cooperative infrastructure. In this case, object detection functionalities are implemented at the infrastructure side by tracking VRU and vehicle trajectories estimated via image processing algorithms. CPM messages are then transmitted by the infrastructure to help interested vehicles identifying possible collision risks. At the cooperative AD vehicle side, the received information is crossed with the locally detected information and given as an input (also in terms of confidence values) to the tactical decision module. Automated soft reactions (like decelerations) as well as hard reactions (like braking) are the outputs of the decision module. Evaluation of this functionality is currently ongoing at the moment of writing this document, and consequently the results are not included (they will be reported in D7.2).
- A functionality for consideration of VRUs interfering with vehicles over an unprotected right turn and seamless integration in the MAVEN cooperative intersection SW architecture. This functionality detects conflicting situations by looking at camera-based recognition of crossing VRUs, prediction of their movements, and consideration of CAVs' intended routes received via V2X. Reaction to possible conflicting situations is done via triggering V2X lane change advices for incoming CAVS. Safety is improved by reducing the probability of rear-end collisions occurrence as a result of reducing the vehicles' stops (especially at non-automated vehicles). Evaluation of this functionality is only possible via simulations because of the limited number of available CAVs and CVs in the project. Nevertheless, motion profiles of the AD vehicle used in real road testing will be analysed after the tests will take place (last integration sprint happening after writing this document). This analysis will allow retrieving, when possible, real world inferences that can enrich the results obtained via simulations. Simulations are currently ongoing at the moment of writing this document, and consequently the results are not included (they will be reported in D7.2).
- A functionality for limiting uneven distribution of vehicles over parallel intersection ingressing lanes and seamless integration in the MAVEN cooperative intersection SW architecture. This functionality detects uneven distributions thanks to various systems (including inductive loops and V2X receptions). Once a suboptimal distribution is identified, the functionality reacts by triggering V2X lane change advices for incoming CAVs. The safety advantage here, even if less pronounced with respect to the previous functionality, is achieved by preventing large imbalance on parallel queues. For the same reason as for the previous functionality, evaluation is done through simulation. Field trials evaluation will be limited to analysis of the AD vehicle motion profiles. Simulations are currently ongoing at the moment of writing this document, and consequently the results are not included (they will be reported in D7.2).
- An enhanced vehicle probing functionality for intersection control embedded in the MAVEN cooperative intersection SW architecture, which supports the previous two functionalities. As described in the document, this new probing approach enhances loop-based adaptive intersection control with floating car data from MAVEN CAM

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

message extensions received from CAVs. The advantages of this solution are particularly visible in high traffic demand scenarios with probing performed over all the intersection approaches.

Regarding the HAD maps, the document has described the iterative evaluation process though which a suitable level of HAD maps precision has been identified to support the MAVEN automated driving scenarios in future tests. For this purpose, commercially available HAD map databases of the test sites, provided by the MAVEN partner TomTom, have been considered. Based on these databases, the requirements for MAVEN vehicles' automation in terms of HAD map format extensions have been identified. In particular, the project has detected the need of a "corridor" representation for road intersections as a pair of "virtual boundary lines" that connect the boundary lane markings of inbound lanes to boundary lane markings of outbound lanes. They are "virtual" because they might not reflect actual lane markings. They are necessary to AD SW system implementations because they provide information about the boundaries to respect to perform a given intersection crossing manoeuvre without invading zones where conflicting manoeuvres with other traffic participants can occur. Once the required extensions have been included in the reference HAD maps, the MAVEN partners have performed an evaluation of the impact of the HAD map accuracy on the AD vehicle trajectory and control calculation. This evaluation demonstrated that the resulting extended HAD maps are suitable for MAVEN automations as they permit trajectory calculation with sufficient quality. As complementary activity, a thorough investigation of the state of the art on HAD map standardization has been performed. This investigation has permitted identifying the minimum set of generic requirements for HAD maps, as well as comparison with the adopted MAVEN HAD map format and extensions. As a result of this comparison, the MAVEN extensions in terms of intersection corridor approach have been identified to be a possible input for standardization.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

References

[1] https://www.c-roads.eu/platform/about/news/News/entry/show/c-its-cooperation-between-c2c-cc-and-c-roads-platform-1.html
[2] Car-2-Car Communication Consortium, "Updates of the C2C-CC Roadmaps", keynote presentation at the 2017 Car2Car Forum, 28 Nov. 2017, available at https://www.car-2-car.org/index.php?id=283:
[3] Car-2-Car Communication Consortium, "C-ITS deployment plans and roadmap", presentation at the CODECS City Pool Workshop #4, 22 March 2018, available at https://www.codecs-project.eu/fileadmin/user_upload/pdfs/City_Pool_Workshop_4/C2C-CC_Deployment_Plan_and_Roadmaps_Rondinone.pdf
[4] MAVEN Deliverable 2.1, "User needs, conceptual design and requirements", Jan 2017
[5] MAVEN Deliverable 5.1, "V2X communications for infrastructure-assisted automated driving", Feb 2018
[6] Rondinone, M., Schindler, J., Blokpoel, R., Walter, T., "V2X communications for infrastructure-assisted automated driving", Fifth IEEE WoWMoM Workshop on Smart Vehicles: Connectivity Technologies and ITS Applications (2018), June 2018
[7] Schindler, J., Dariani, R., Rondinone, M., Walter, T. (2018) *Dynamic and Flexible Platooning in Urban Areas.* AAET Automatisiertes und vernetztes Fahren, 14.-15. März 2018, ITS mobility, ISBN 978-3-937655-44-4.
[8] MAVEN Deliverable 2.2, "System architecture, specifications and verification criteria", Feb 2017
[9] Hagen Saul, Marek Junghans, Kay Gimm, Risk Estimation of Interactions of Right Turning Vehicles and Vulnerable Road Users, 11th International Conference on Risk Analysis and Hazard Mitigation, June 2018.
[10] MAVEN Deliverable 4.1, "Cooperative adaptive traffic light with automated vehicles", Jan. 2018
[11] ETSI draft TR 103 299, v1.0.1, Intelligent Transport System (ITS); Cooperative Adaptive Cruise Control (C-ACC); Pre-standardization study, Jan. 2018
[12] ETSI draft TS 103 300-2 Intelligent Transport System (ITS); Vulnerable Road Users (VRU) awareness; Part 2: Functional Architecture and Requirements definition, under development
[13] ETSI TS 101 539-2 Ver. 1.1.1, Intelligent Transport Systems (ITS); V2X Applications; Part 2: Intersection Collision Risk Warning (ICRW) application requirements specification, June 2018
[14] 5G PPP, "5G Automotive Vision" white paper, Oct. 2015. Available at https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-White-Paper-on-Automotive-Vertical-Sectors.pdf
[15] ISO 14825:2011, Intelligent transport systems -- Geographic Data Files (GDF) -- GDF5.0, July 2011
[16] ISO/TR 21718:2017, Intelligent transport systems -- Spatio-temporal data dictionary for cooperative ITS and automated driving systems, Nov. 2017
[17] ISO/CD 17572-4, Intelligent transport systems -- Location referencing for geographic databases -- Part 4: Lane-level location referencing, under development
[18] ISO 14296:2016, Intelligent transport systems -- Extension of map database specifications for applications of cooperative ITS, Feb. 2016
[19] ETSI EN 302 895 Ver. 1.1.1, Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Local Dynamic Map (LDM), Sept 2014
[20] OGC, OGC® Land and Infrastructure Conceptual Model Standard (LandInfra), Dec 2016. Available at http://docs.opengeospatial.org/is/15-111r1/15-111r1.html

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

[21] OpenDRIVE®, http://www.opendrive.org/
[22] RoadXML, https://www.road-xml.org
[23] NDS association, https://www.nds-association.org
[24] ISO/TS 21219-21:2018, Intelligent transport systems -- Traffic and travel information via transport protocol experts group, generation 2 (TPEG2) -- Part 21: Geographic location referencing (TPEG-GLR), April 2018
[25] ISO 14819-3:2013, Intelligent transport systems -- Traffic and travel information messages via traffic message coding -- Part 3: Location referencing for Radio Data System -- Traffic Message Channel (RDS-TMC) using ALERT-C, Dec. 2013
[26] ISO 17572-3:2015, Intelligent transport systems (ITS) -- Location referencing for geographic databases -- Part 3: Dynamic location references (dynamic profile), Jan. 2015
[27] ISO/TS 21219-22:2017, Intelligent transport systems -- Traffic and travel information (TTI) via transport protocol experts group, generation 2 (TPEG2) -- Part 22: OpenLR location referencing (TPEG2-OLR), June 2017
[28] SAE J2374_199907, Location Referencing Message Specification, July 1999
[29] SAE J2266_2004106, Location Referencing Message Specification (LRMS), Oct 2004
[30] SAE J1746_1999126, ISP-Vehicle Location Referencing, Dec 1999
[31] SAE J2735_201603, Dedicated Short Range Communications (DSRC) Message Set Dictionary, March 2016
[32] MAVEN Deliverable 6.1, "Integration of basic hardware into test vehicles", Dec 2017
[33] MAVEN Deliverable 6.3, "Intermediary report of the integration", May 2018
[34] Richter, Andreas and Scholz, Michael (2018). Improving Road Network Surveying in the Automotive Development Process through Road2Simulation Guidelines. *Transport Research Arena (TRA) 2018, 16.-19.* Apr. 2018, Austria
[35] Simple Feature Access - Part 1: Common Architecture, http://www.opengeospatial.org/standards/sfa
[36] MAVEN Deliverable 6.2, "Installation and adaptation of the road side", Dec 2017
[37] https://www.nvidia.de/object/cuda-parallel-computing-de.html
[38] ETSI EN 302 637-2 Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service, V1.3.2 (2014-11)
[39] Blokpoel, R., Vreeswijk, J., Krajzewicz, D., Kless, T., "Unified Evaluation Method for Traffic Control Algorithms". Proceedings of the ITS World congress, Detroit, U.S.A, Sept 2014
[40] Blokpoel R., Vreeswijk J., "Uses of probe vehicle data in traffic light control", In Proceedings of 6th Transport Research Arena, 2016
[41] DLR Institute of Transportation Systems (2016). AIM Data Services. *Journal of large-scale research facilities, 2*, A73. http://dx.doi.org/10.17815/jlsrf-2-124
[42] TomTom International BV, RoadDNA Product Info, available at http://download.tomtom.com/open/banners/RoadDNA-Product-Info-Sheet-1.pdf
[43] Stuiver, A., & Blokpoel, R. (2016). *Sensory observation message and CAM extensions for VRU safety*. Paper presented at 11th European Congress and Exhibition on Intelligent Transport Systems and Services, Glasgow, United Kingdom.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690727. The content of this document reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.