D5.2

V2X-based cooperative sensing and driving in Transition Areas

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Editor / Main Author	Alejandro Correa	UMH
Reviewer	Robbin Blokpoel Xiaoyun Zhang	DYN
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Editor / Main author

Alejandro Correa (UMH)

List of contributors

Franz Andert (DLR), Robbin Blokpoel (DYN), Nicolai Wojke (DLR), Gokulnath Thandavarayan (UMH), Baldomero Coll (UMH), Miguel Sepulcre (UMH), Javier Gozalvez (UMH), Anton Wijbenga (MAP), Julian Schindler (DLR), Sven Maerivoet (TML), Xiaoyun Zhang (DYN), Andreas Leich (DLR), Clarissa.Boeker (DLR)

List of reviewers

Robbin Blokpoel (DYN)

Xiaoyun Zhang (DYN)

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■ PU : Public

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Executive Summary

The objective of the TransAID (Transition Areas for Infrastructure-Assisted Driving) project is to deal with situations that cooperative and automated vehicles (CAV) might face when they are approaching to traffic conditions or zones that their automated systems are not able to handle by themselves. In those cases, the driver will be required to take control of the vehicle; this is the so-called Transition of Control (ToC). TransAID develops and demonstrates traffic management procedures and protocols to increase the overall traffic safety and efficiency specially at transition areas (i.e. zones where ToCs should take place) considering the coexistence of CAVs, autonomous vehicles (AVs), cooperative vehicles (CVs) and legacy vehicles (LV). TransAID measures require the use of communications between vehicles (V2V), and between vehicles and the road infrastructure (V2I) which are mainly used to gather information about the traffic stream through cooperative sensing and to support in the coordination of the vehicles maneuvers through cooperative maneuvers. In this context, this document shows the sensor devices and techniques to fuse their data that are being developed in TransAID. This includes techniques implemented at camera-equipped infrastructures that are able to detect, create bounding boxes and uniquely track objects using optical flow, and at the vehicle employing a hybrid sensor fusion strategy which contains a low-level LIDAR fusion module, that transforms the sensor data of multiple laser scanners into a common coordinate system, and an object-level fusion module, that fuses in-vehicle sensor data with data coming from neighbouring vehicles. The document also shows the cooperative techniques that are being designed to enable the Collective Perception Service (CPS) in line with ETSI. The ETSI's CPS entails the continuous exchange of Collective Perception Messages (CPM) that include a logic representation of the objects detected by the sensors and which are useful to improve the vehicles' and the infrastructure's perception of the driving environment. A key aspect for the efficient execution of the CPS is the definition of appropriate generation rules for the transmission of the CPMs, i.e. how often they are transmitted and what information do they include. This document includes a comprehensive analysis of the effect on the communications performance and information awareness of different CPM generation rules that are being considered in ETSI. The conducted analysis has shown that there is a trade-off between perception capabilities and communications performance/scalability: vehicles detecting the same object(s) and including them in their CPMs create redundant detection which can help improve the perception capabilities but generate higher channel load levels and therefore impact the performance of V2X networks. In the framework of TransAID, advanced policies have been proposed to further optimize the CPM, both its content and transmission triggering conditions, in order to achieve the necessary levels of redundancy and minimize the impact of the implementation of CPM in the stability and scalability of future V2X networks. In particular, four different methods have been designed: a) the look ahead mechanism that reduces the number of CPM transmitted with a small number of objects by the prediction of objects that will need to be transmitted in a near future; b) the redundancy mitigation mechanism that reduces the size of the CPMs and thus increases reliability by limiting the transmission of objects that have been recently transmitted by a neighbour vehicle and c) two different proposals for the combination of previous methods that enhance the performance of collective perception.

In addition, this document investigates existing cooperative driving mechanisms, and specially the ETSI approach on manoeuvre coordination. The ETSI's Manoeuvre Coordination Service (MCS) is defining new concepts and messages which can be used to coordinate manoeuvres between vehicles. TransAID is actively participating in this process, e.g., by means of the definition of the Manoeuvre Coordination Message (MCM) and extending the role of the infrastructure to support the vehicles' manoeuvres coordination under certain scenarios and conditions. In this context, this document presents the message flow for the set of services that are being considered in TransAID.

First, this document has analysed the traffic management measures defined by the different services of the TransAID project, and the required message flow for each service has been defined. Each message flow describes how, when, and where the vehicles communicate between them, and between them and the infrastructure, to execute the traffic management measures. Then, this document provides an analysis of the MCM generation rules. As highlighted for the CPMs, MCM messages should be transmitted with a frequency high enough to guarantee that the vehicles' manoeuvre coordination is possible. However, a too frequent exchange of MCM messages can increase the channel load to the point that it can negatively impact the performance and scalability of the V2X network. The conducted analysis has shown the importance of considering the vehicular context for the generation of the MCM messages in order to achieve a good balance between channel load and reliability for a safe execution of the cooperative manoeuvres. In particular, two main MCM generation rules approaches have been developed: a) the risk approach that measures the risk of vehicles with their neighbours and adapts the transmission rate based on the risk; b) the tracking trajectories approach that measures the variations between the trajectories transmitted by a vehicle and only sends a new message when the variation is significant. The analysis performed showed that the benefits of both approaches as the risk approach increases the possibilities of successful coordination while the tracking trajectories approach performs an efficient use of the communications channel while keeping neighbours updated about any change in the trajectory.

1 Introduction

1.1 About TransAID

The introduction of Automated Vehicles (AVs) is expected to improve traffic safety, reduce fuel consumption and improve traffic efficiency. To do so, automatization of perception and control tasks is employed with the aim of outperforming the capabilities of human drivers. The efforts of the automotive industry are focused on preparing future AVs to support an increasing number of road conditions and traffic situations. However, there will be situations where the automated systems will reach their functional limits and will not be able to handle specific traffic situations on their own [1]. In these situations, a Transition of Control (ToC) to manual driving will be required. The duration of a ToC will be influenced by the time required by the driver to recover full situation awareness and safely take over control of the vehicle. This time increases in higher automation levels, where drivers are allowed to perform non-driving related secondary tasks. If the driver is not able to take over control of the car, the automated vehicle will perform a so-called Minimum Risk Manoeuvre (MRM) to bring the vehicle into a safe spot (e.g. decelerating to full stop, or change lane to occupy a safe spot [2]. There will be areas and situations on the roads where high automation can be granted, and others where it will not be allowed or feasible due to system failures, highly complex traffic situations, human factors and possibly other reasons. At these areas, many AVs will have to perform ToCs. We refer to these areas as “Transition Areas” (TAs).

TransAID develops and demonstrates traffic management procedures and protocols to enable smooth coexistence of cooperative and automated vehicles (CAVs), AVs of different SAE (Society of Automotive Engineers) levels, cooperative vehicles (CVs) able to communicate via vehicle-to-anything (V2X), and legacy vehicles (LVs), especially at TAs. A hierarchical and centralized approach is adopted, where control actions are implemented at different layers including Traffic Management Centres (TMC), roadside infrastructure, and vehicles. Following this approach, in the TransAID project, different services have been defined addressing specific complex traffic situations at Transition Areas. The road infrastructure supports the coordination of manoeuvres of vehicles by providing advices, notifications or information to vehicles in order to increase the overall traffic safety and efficiency.

To validate the effectiveness of the traffic management measures developed at the TransAID project, simulations taking into account traffic safety and efficiency metrics will be performed. For the simulations to be as reliable as possible, the most relevant microscopic traffic models for mixed traffic behaviour and interactions with Automated Driving (AD) cars are developed [3]. Also, communication protocols for the cooperation between CAVs, CVs, and Road Side Units (RSUs) are implemented, modelled and included. Based on the results of these simulations, the most promising solutions are then implemented as real-world prototypes and demonstrated in closed and controlled environments as proof of concepts for real world’s technical feasibility

1.2 The TransAID iterative approach

The hierarchical and centralized approach of the TransAID project is applied over two iterations, each taking half of the project’s total duration. During the first iteration, the focus is on studying aspects of transition of control and transition areas through basic scenarios. This implies that realistic models for AD (automatic driving) and communication protocols need to be developed and/or adopted to cover the requirements of these scenarios’ simulations. Using the basic scenarios, it is possible to run initial simulations and focus in detail on the relatively new aspects of ToCs, TAs and measures mitigating negative effects of ToCs. The goal of the first iteration is hence to gain experience with all aspects relevant to TAs and mitigating measures. In the second iteration, the gained experience is used to improve/extend the traffic management measures while at the same time increasing the complexity of the investigated scenarios (e.g. including more challenging scenarios not considered in the first iteration, or combining multiple scenarios in the same evaluation). The second iteration will consequently need additional functionalities from the traffic and communication protocols point of view, whose modelling will be implemented at later stages.

1.3 Purpose of this document

The TransAID consortium has selected five services to be implemented in the first iteration of the project. These services define traffic management measures that require the use of communications between vehicles and between vehicles and the road infrastructure. In particular, the traffic management measures defined at the TransAID project employ communications for two main tasks: gathering information about the traffic stream through cooperative sensing and support in the coordination of the vehicles manoeuvres through cooperative manoeuvring.

In this document, we elaborate on the cooperative sensing and driving aspects of the traffic management measures for the TransAID services. On one hand, this document first describes the different types of sensors that can be available at the vehicle side and at the infrastructure side. It also presents novel mechanisms for the fusion of sensor information at the vehicle and at the infrastructure. TransAID services employ cooperative sensing (referred to as collective perception in ETSI (European Telecommunications Standards Institute)) to improve the vehicles' and infrastructure's perception of the driving environment through the exchange of sensor information. ETSI is currently defining the so called Collective Perception Service (CPS), and the current focus is on the definition of the appropriate generation rules of the Collective Perception Message (CPM). A comprehensive analysis of the effects of different generation rules in terms of communications and information awareness has been done in TransAID employing advanced communications simulation tools, and has been presented and discussed at ETSI meetings to contribute to the standardization process (see Annex A). On the other hand, this document also defines the message flows between vehicles, and between vehicles and the road infrastructure necessary to implement the cooperative driving manoeuvres specified in the traffic management measures of the different TransAID services. ETSI is also defining the so called Maneuver Coordination Service (MCS). The current concept proposed at ETSI has been extended in TransAID to include the support of the infrastructure in the coordination of the cooperative manoeuvres of vehicles. The TransAID proposal for the MCS has also been presented and discussed at ETSI meetings to contribute to the standardization process (see Annex A). Furthermore, different types of MCM generation rules have been designed and an in-depth analysis has been done showing their benefits and disadvantages both in terms of communications and performance of cooperative manoeuvring.

The definitions of the cooperative sensing and driving mechanisms presented in this document are based on the V2X Facilities layer message set defined in Deliverable 5.1 [4]. The work conducted has also taken into account the traffic management measures defined in WP4 (see Deliverable 4.2 [5]) and the cooperative manoeuvres modelled in WP3 (see Deliverable 3.3 [6]). The message flow defined in this document will be employed in the traffic and communications simulations of WP6 and the real world testbed of WP7.

1.4 Structure of this document

This document is divided into two main blocks aligned with the two tasks (task 5.2 and task 5.3 of WP5) that directly contributed to the developments described here. The outputs of task 5.2 are presented in Section 2 while the outputs from task 5.3 are shown in Section 3. Both clearly identify the work done in the first and second iteration of the project.

Section 2.1 describes the state of the art of cooperative sensing including information about the types of sensors employed at vehicles and at the infrastructure. It reviews the current status of the standardization of the CPS. Section 2.2.1 presents the work done in the first iteration in terms of novel cooperative sensing mechanisms that enhance the overall environmental perception. Section 2.2.2 presents a comprehensive analysis of the CPM generation rules that take into account the improvement of the CPM in terms of information awareness and the feasibility of the transmission of CPMs in terms of communications. Similarly, Section 2.3 presents the update done in the second iteration to the development of cooperative sensing mechanism (Section 2.3.2) while Sections 2.3.2 and 2.3.3 presents the TransAID approach for CPM generation rules that improve the current ETSI CPM rules in terms of channel usage, object awareness and redundancy mitigation.

Similarly, Section 3.1 describes the state of the art of cooperative driving, the current status of the standardization of the MCS and the TransAID proposal for the MCS. Section 3.2.1 describes the message flow needed to execute the traffic management measures of the TransAID services in the first iteration. Section 3.2.2 describes the message flow needed for the execution of a cooperative lane change following the TransAID approach for the MCS. A preliminary analysis of the MCM generation rules in terms of the channel load is presented in Section 3.2.3. The work done in the second iteration is shown in Section 3.3. First, the message flows needed for the execution of the TransAID services in the second iteration are described in Section 3.3.1. Section 3.3.2 focuses on the design of a set of generation rules for the MCM. Different proposals for generation rules have been described and analysed in detail to study their performance and use of the communications channel. Finally, Section 4 briefly concludes the deliverable and summarizes the main results obtained.

1.5 Glossary

Abbreviation/Term	**Definition**
AD	Automated Driving
AID	Automatic Incident Detection
AoI	Area-of-Interest
AV	Automated Vehicles
CAM	Cooperative Awareness Message
CAS	Cooperative Awareness Service
CAV	Cooperative and Automated Vehicle
CBR	Channel Busy Ratio
C-ITS	Cooperative Intelligent Transport Systems
CoG	Centre of Gravity
CPM	Collective Perception Message
CPS	Collective Perception Service

CSM	Cooperative Sensing Message
CV	Cooperative Vehicle
DCC	Decentralized Congestion Control
DE	Data Element
DENM	Decentralised Environmental Notification Message
DF	Data Field
DX.X	Deliverable X.X
EPM	Extended Perceived Message
ETSI	European Telecommunications Standards Institute
FoV	Field-of-View
GNSS	Global Navigation Satellite System
HMI	Human Machine Interface
INS	Inertial Navigation System
ITS	Intelligent Transport System
ITS-G5	Access technology to be used in frequency bands dedicated for European ITS
ITS-S	ITS station
LV	Legacy Vehicle
MC	Management Container
MCM	Manoeuvre Coordination Message
MCS	Manoeuvre Coordination Service
MRM	Minimum Risk Manoeuvre
MTU	Maximum Transfer Unit
ORC	Originating RSU Container
OSC	Originator Station Container
OVC	Originator Vehicle Container
PDF	Probability Density Function

PDR	Packet Delivery Ratio
PER	Packet Error Rate
POC	Perceived Object Container
PSR	Packet Sensing Ratio
RoI	Region-of-Interest
RSU	Road Side Unit
SAE	Society of Automotive Engineers
SDC	Station Data Container
SIC	Sensor Information Container
SLAM	SImultaneous Localization And Mapping
SUMO	Simulation of Urban MObility
TA	Transition area
TMA	Traffic Monitoring Area
TMC	Traffic Management Centre
ToC	Transition of Control
ToR	Take-over Request
TransAID	Transition Areas for Infrastructure-Assisted Driving
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
WP	Work Package

2 Cooperative Sensing

Automated vehicles are equipped with multiple exteroceptive sensors (e.g. LIDARs, RADARs, sonars and cameras) to perceive their local environment, and thereby perform control operations and execute Intelligent Transport System (ITS) services. This local perception information makes the AVs aware of objects (e.g. other vehicles, trees, cyclist, roadside rocks, etc.) that are present in the driving environment. However, the perception capabilities of each sensor are limited to a certain detection range and a given Field-of-View (FoV). In addition, these capabilities can be impaired due to the presence of obstacles (obstructions) in the field of view, sensors blind spots, adverse weather conditions and sensitivity to ambient light and temperature, among others. These limitations can significantly degrade the perception capabilities of AVs, and hence negatively influence their safety and driving efficiency. For example, it could limit the demands of the AV systems to detect objects present in its Region-of-Interest (RoI) or Area-of-Interest (AoI). [7] and [8] define this AoI/RoI to be equal to 300 meters for performing safety applications in AVs. This range is hard to achieve with the current exteroceptive sensors' FoVs.

CAVs can improve their perception capabilities thanks to the exchange of sensor information using wireless technologies such as IEEE 802.11p/ITS-G5 [9] or C-V2X/LTE-V [10]. This is generally referred to as collective perception or cooperative sensing. Collective perception enables CAVs to improve their perception of the surrounding environment by receiving information from other vehicles and/or infrastructure nodes about objects that are beyond their sensing range. It can also improve CAVs' detection accuracy and increase the confidence about the detected objects. Collective perception can also help mitigate the negative impact of adverse weather conditions on the sensing capabilities as well as the initial limited CAV market penetration rate. The collective perception concept can also be extended to infrastructure nodes with ITS sensing capabilities. These nodes can transmit and receive sensor information to/from vehicles to improve their respective knowledge of the driving environment. Collective perception enables the exchange of sensor information to improve their perception of the driving environment. It enables vehicles (and the infrastructure) to detect objects, e.g. non-connected vehicles, pedestrians, cyclist, obstacles, etc., beyond their local sensing capabilities. By improving the vehicles' perception of the driving environment through the exchange of sensor information, collective perception seeks improving the safety and traffic efficiency of connected and automated vehicles.

In general, the cooperative sensing or collective perception process has shown to include and rely on a set of functionalities that are illustrated in Figure 1. First, the cooperative sensing benefits from the sensors (vision, LIDAR, RADAR, sonar), and the data they provide, that AVs utilize to perform automated operations and to manage the necessary control operations. In the collective perception process, this data is enriched (new data/objects, and increased accuracy and confidence about the detected data/objects) when it is fused with sensor data received from neighbouring CAVs/infrastructure. Then, the 'detection & fusion' function processes and fuses the data acquired by the in-built sensors. This function aims at identifying objects by analysing features like edges, regions and attributes, and saving them in a local database. The 'message generation' takes the locally stored perception information to form the collective perception messages (this could include fused information or sensor specific object data). It should be noted that the information included in the collective perception messages could be of any nature: raw sensor data [11] (this is not practical though), or processed objects with a specific description format [12]. The nature of the data to be transmitted can be decided based on existing trade-offs between the data size, processing cost and resolution/accuracy. Another important aspect of the 'message generation' function is to decide when vehicles should exchange the collective perception messages. This decision is made considering the defined generation rules, as indicated above. Finally, the 'congestion control' function acts as a gatekeeper before the messages are transmitted through the radio unit. In particular, the ‘congestion control’ function is designed to avoid the saturation/congestion of the communications channel. To this aim, the ‘congestion control’ function can perform rate, flow and/or power control strategies to maintain the channel congestion level at a certain level (or below a defined threshold).

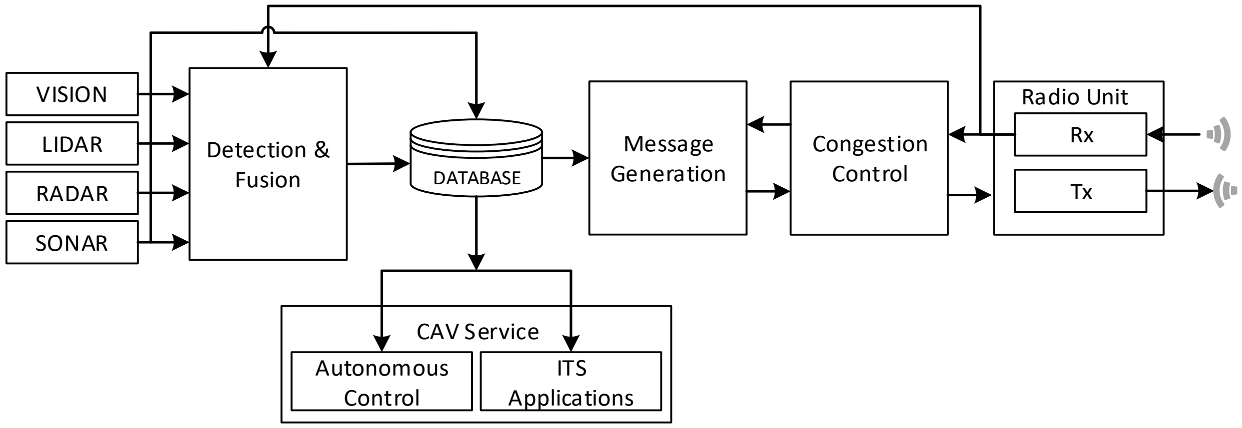


Figure 1. Collective Perception Functionalities.

The ETSI Technical Committee on ITS is currently developing the European standards for collective perception or cooperative sensing. They are defining a new module at the Facilities layer referred to as collective perception service to enable the exchange of sensor information about the status and dynamics of detected objects. The standardization process will define which information should be exchanged about the detected objects, and how often it should be exchanged. In particular, ETSI is currently designing the V2X message (known as Collective Perception Message) necessary for vehicles to exchange sensor information about the status and dynamics of detected objects. Another important aspect yet to be decided is the CPM generation rules that define when vehicles should exchange CPM messages. These generation rules will have a significant impact on the effectiveness of the collective perception service and on the wireless vehicular network. In fact, if vehicles exchange information about detected objects very frequently, they will significantly improve their perception capabilities and be able to detect their surrounding objects with higher accuracy. However, a too frequent exchange of CPM messages can also saturate the communications channel to the point that these messages cannot be transmitted, ultimately reducing the effectiveness of the collective perception service.

The rest of this section is organized as follows. Section 2.1 presents the current state-of-the-art on cooperative sensing. Given the importance of the sensors for the collective perception process, section 2.1.1 first reviews the type of sensors that are currently available in the CAVs and the infrastructure, and existing techniques to fuse the data these sensors generate. Section 2.1.2 then summarizes existing studies on collective perception conducted to date. This includes an analysis of the current efforts on the ETSI standardization of the CPS, the CPM message, and generation rules. Sections 2.2.1 and 2.2.2 then show the main contributions of TransAID to progress the current state of the art. In particular, Section 2.2.1 presents the techniques and models developed under TransAID to enable the sensor data fusion at the infrastructure and vehicles. Section 2.2.2 analyses, under different driving conditions, the performance and efficiency of different CPM message generation rules that are currently discussed at ETSI. This analysis has been presented at ETSI to contribute to the standardization process (see Annex A). Section 2.3 shows the research conducted by the TransAID project in the second iteration. Section 2.3.1 describes the new version of sensor fusion algorithms developed in the project whereas Section 0 and Section 2.3.3 focus on the impact of CPM generation rules on the performance of cooperative sensing. In particular, two new algorithms have been developed and analysed in detail in Section 0. Section 2.3.3 presents two different proposals for the combination of the developed algorithms that improve the overall performance of collective perception.

2.1 State of the art

2.1.1 Sensor information

CAVs require a comprehensive model of the environment for safe automated operation. In a collective perception environment, this model is generated from sensors mounted not only on the ego-vehicle itself but also from data acquired by other CAVs as well as other CVs and road infrastructure. CPM defines a V2X message for the exchange of such information in the form of an abstract description. This description must be generated from the raw sensor data in a pipeline of sensor-specific processing steps and, at the receiving end, the world model must be enriched with the abstract description of other ITSs. Fusion of different sensor sources must happen under consideration of involved sensor uncertainties in order to generate a fused environment model with increased accuracy compared to the single sensor model. This section reviews existing and upcoming sensor configurations with regard to the information exchange via CPM in TransAID. In addition to that, cooperative traffic will be investigated, e.g. by using CAM messages [14] and others if available.

2.1.1.1 In-vehicle sensors

2.1.1.1.1 Environment sensing and ego-localization

Considered are exteroceptive sensors which gather information about the environment at some range. Typical sensors and their possibilities by state-of-the art processing techniques are:

- Monocular camera: image and video, image differences, angular information of tracked objects, possible full 3D info when projection to ground is possible,
- Stereo camera: as monocular camera, plus range information through depth images. Range depending on camera distance, typically 2-30m at 30cm baseline,
- Active cameras (Time of Flight / Photo mixer device): typically camera with rather low pixel resolution, plus near range depth (<10m),
- SONAR: distance of object (usually without identifying it) within field of view, range typically 0-3m,
- RADAR: distance of object, typically including identification. can be high-range (200m+) depending on sensor,
- LIDAR: rather high-resolution 3D point cloud from measured object distances, including object identification and tracking, various range types from 30m to 200m possible. Various types of fields of view (e.g. single distance spot, single line scanning, multiple line scanning, 360° rotating FOV).

Together with environment sensing, ego-location, velocity (linear and angular) and timing will be required in most use cases. Position and timing are typically available through Global Navigation Satellite System (GNSS), plus optional inertial navigation systems (INS). Sources like map matching, wheel odometry or environment sensor-based techniques (landmark navigation, Simultaneous Localization And Mapping (SLAM), visual odometry) can be an extension alternative to GNSS positioning. Such techniques are important on GNSS position dropouts (e.g. signal interruption, multi-path, jamming) and when relative navigation (e.g. within legacy traffic flow, narrow track guidance) is required. For a typical GNSS/INS, the outputs are:

- 3D geodetic position (e.g. WGS84 or UTM plus ellipsoidal or geoid height), optional RTK with improved accuracy augmentation (SBAS, GBAS, DGNSS),

- 3D velocity estimate,
- precise time,
- heading estimate on multi-antenna receivers,
- 3D attitude and high-frequent position and velocity updates when using GNSS/INS strapdown,
- 3D acceleration and turn rates with INS,
- uncertainty estimates by GNSS DOP and filter covariance.

Depending on the application context, state information is often reduced (e.g. only 2D position and heading for ground transportation, plus their derivatives) and can also be locally centred (e.g. Cartesian position relative to lanes or other infrastructure).

2.1.1.1.2 Example Configuration

On the vehicles, GNSS navigation and environmental object data (at most from image, RADAR or LIDAR-based identification and tracking) is taken into account. This will generally provide two message types:

- Cooperative Awareness Message (CAM) (generated from GNSS or GNSS/INS and static vehicle parameters),
- Collective Perception Message (generated from object data from at least one environmental sensor linked to GNSS/INS).

Testing configurations are described in D7.1 [13]. The configuration is generally based on DLR's vehicle availability and installed hardware – currently this comprises multiple and co-calibrated LIDARs (currently three at front and one at rear) with altogether almost 360° FOV (except some gaps at the vehicle sides). Optionally, one front RADAR, and cameras can be taken into account if advantageous. Navigation and timing data are obtained by a NovAtel GPS/INS solution. Depending on the testing area, precise RTK which uses self-operated DGPS or SAPOS can be used.

2.1.1.2 Infrastructure-mounted sensors

2.1.1.2.1 Inductive loop

The default sensor for infrastructure-based detection is the inductive loop. The detection principle is based on the increase of inductance of a coil when a metal core is added, the magnetic field lines are shown in the sketch below:

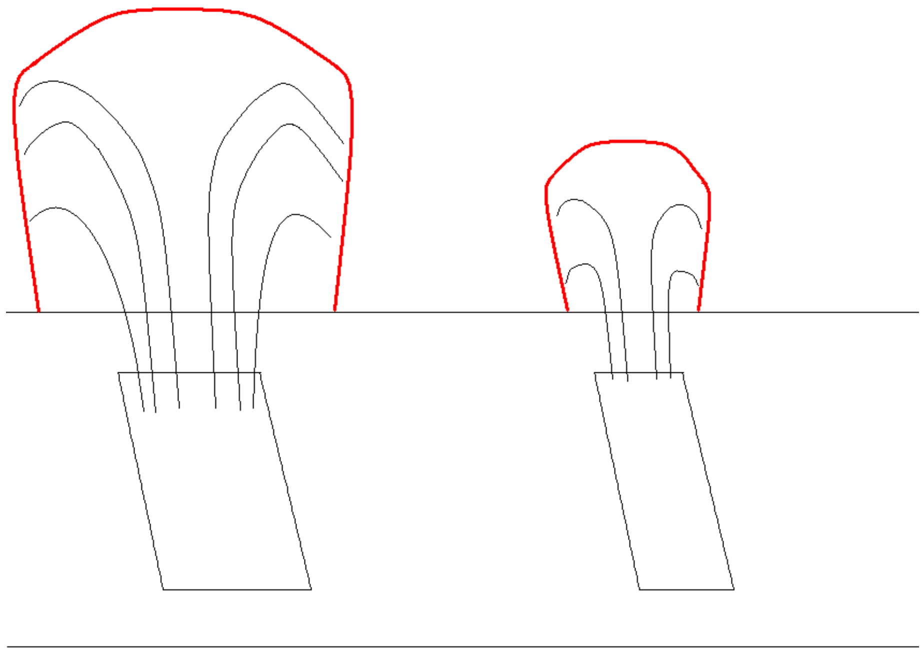


Figure 2. Magnetic field around inductive loop.

Figure 2 shows that a smaller loop has a smaller reach of the field lines and will therefore behave differently when a vehicle with a high ground clearance passes over it. While smaller loops are more precise in detecting vehicles at a particular location, making the loop too small may result in problems detecting trucks and agricultural vehicles. For motorway systems the default size of a loop is 1.5m x 1.8m (1.5 is the length in the driving direction), while urban systems use 1.0m x 2.0m, but it should be noted there is a high variety for urban systems in loop design, where even parallelogram shapes are often used.

In the figure below the amplitude of the relative inductance change over time is shown for a common private car (Volvo V40 early 2000 model), this pattern is referred to as the "vehicle signature":

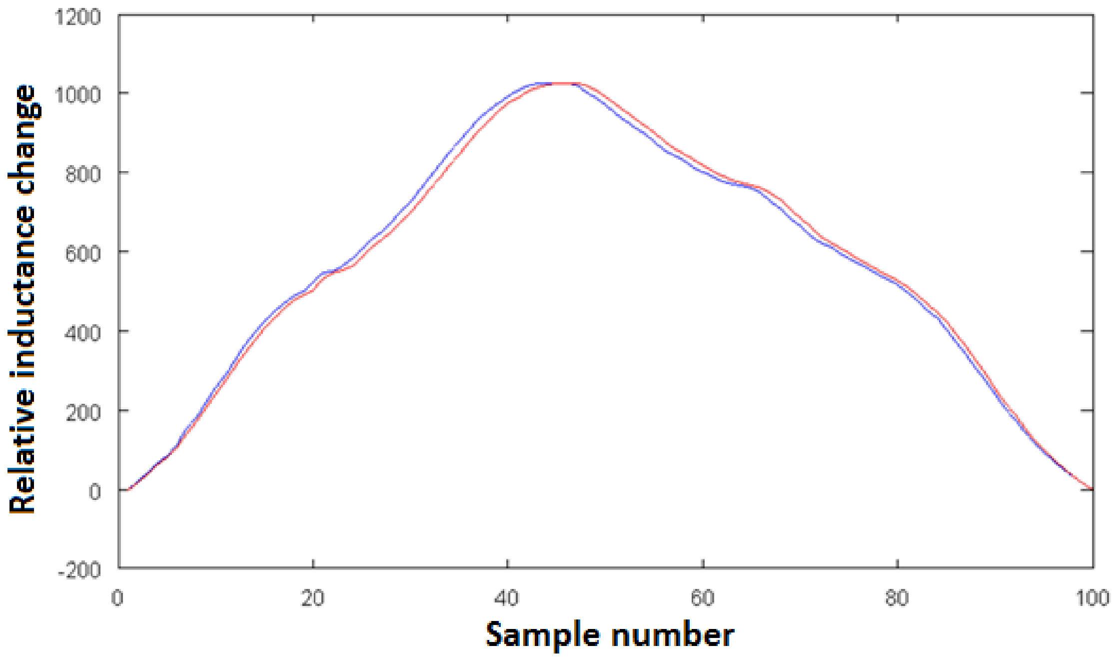


Figure 3. Vehicle signature generated by passing over an inductive loop.

The data was captured on a double loop while the vehicle was accelerating; the first vehicle signature is indicated by the blue graph, the second by the red. The detector card was set to sample the relative inductance change every 3ms, resulting in 100 samples of the vehicle passage that could be considered above noise level.

The double loop is an interesting case because vehicle speed can be measured instead of estimated based on an assumption of the vehicle length. The duration of the loop output being over a certain value, i.e. the signature length, depends on both the vehicle length and the speed, so for a single loop this has to be estimated as both variables are unknown. In order to measure the speed on a double loop, the time difference for a reference point in the signature is used. Common references are Centre of Gravity (CoG), rising/falling flank and peak value.

While presence detection is easy with a close to 100% accuracy given proper loop placement and dimensions, the speed has some inaccuracy due to noise and deformation of the signature. Therefore, this accuracy is 97% or higher for Dynniq hardware (certified by the Dutch authority called "Nederlands Meetinstituut"). Cyclists and motorcycles have a very low metal content, especially with upcoming carbon technologies, and can sometimes be missed by detectors.

Theoretically, it would also be possible to measure the acceleration of a vehicle by comparing the deformation of the signatures or analysing the difference in travel time between the rising and falling flank. This has not yet been integrated in existing hardware due to low market demand for such a feature.

2.1.1.2.2 RADAR and video sensors

Due to inductive loops being the standard solution, both video and RADAR detectors follow the same principle and draw a virtual loop inside the field of view for detections.

In case a vehicle is inside the area of a loop, the infrastructure gets the signal "occupied" just like for the real induction loop. Problems arise with extreme weather and small errors can be made when birds pass in front of the camera. Sensor occlusion is a problem for any sensor that does not observe the traffic on a perpendicular angle to the road surface; this happens mostly for detection of private cars behind tall trucks. Calibration and positioning of the sensor are therefore very important to minimize this.

In general, infrared is less sensitive for extreme weather conditions and has the best performance for cyclist detection. Visible light is the cheapest technology but suffers from extreme weather, sun glare and is more difficult to filter for specific vehicle classes. RADAR is more accurate with moving objects while cameras are more accurate for stopped objects. Therefore, the *TrafiRADAR* is a promising new sensor that combines RADAR with visible light detection to track vehicles on a stretch of road, determining their position and speed.

According to factory specifications, these sensors all have a very high accuracy >98%, which is measured under ideal circumstances and can be disappointing in real-world scenario's. Therefore, it is recommended to search for independent evaluations or practitioners experience before deployment.

2.1.1.2.3 Example configuration

As the vehicle configurations, the testing RSU camera setup is described in D7.1 [13]. Bases are off-the-shelf surveillance cameras to be mounted with FOV towards the testing area, together with networking and V2X hardware.

Dutch motorways generally have an inductive loop pair installed every 600-1000 meter in conjunction with a gantry with panels that warn drivers for traffic jams. This is part of a so-called Automatic Incident Detection (AID) system. The distance between the gantries varies depending on the location of curves, bridges and viaducts, because there should always be line of sight with one set of panels for traffic. Without specific conditions, the distance is 800 meter.

In urban areas, there are several types of loops installed. The most common is the stop line detector, which detects whether a vehicle is waiting for a specific signal. If this is not the case, the signal can be skipped for dynamic controllers. Once a traffic light is green, it can also be used to detect when the queue has cleared and the light can switch to amber and red again. However, this is not very efficient because a margin of approximately 2 seconds is required to be certain there is no vehicle that accelerated a bit slower left behind. This means that the light switches to amber 2 seconds after the last vehicle left the queue. More efficient is to put a large detector a bit further upstream. Typically, these detectors have a length of 20-40 meter in the driving direction and are placed 20m upstream. The large length means that there is no time margin required anymore to cover the gaps between vehicles. Placing it a bit upstream means that as soon as the last vehicle leaves the loop, the light can switch to amber, while the vehicle is so close that it won't stop anymore. Effectively, the green phase can be 3-5 seconds shorter with such detectors. More advanced controllers that model the vehicles approaching the intersection also require upstream entry detection. These are again smaller loops of 1 meter in the driving direction to enable counting. In urban networks with consecutive intersections, the entry detection is effectively an exit detection of an upstream intersection.

2.1.1.3 Sensor fusion

Automated vehicles are typically equipped with a variety of sensors, which each has different properties in respect to reliability in different weather conditions, accuracy and precision, viewing range and resolution (see D7.1 [13]). Sensor fusion algorithms are used to combine measurements from different sensor sources in a way that the combined output is of higher quality than the output of each individual source. Therefore, a good sensor fusion algorithm levels out weaknesses of the individual sensors based on a-priori knowledge about the involved sensors and physical constraints that allow assessing if an object hypothesis is found or not, for example based on known object motion models and calibration parameters. The mathematical framework behind most sensor fusion algorithms applies probabilistic reasoning on the uncertainty of individual sensors and object motion models, for example using Kalman filtering or Bayesian networks [15].

The sensor data that is shared between ITS stations (ITS-Ss) in a collaborative perception environment can be regarded as additional sensor sources that (a) increase the field of view of individual ITS-S and (b) reduce the uncertainty associated to individual object hypotheses. As such, the shared information can be incorporated into the environment perception as part of the sensor fusion architecture similar to sensors which are directly connected to the ITS-S in hardware. The remainder of this section summarizes different sensor fusion architectures and reviews possibilities for the integration of collaborative perception data via CPM.

2.1.1.3.1 Sensor fusion architectures

Existing sensor fusion architectures can be categorized according to the level in the processing chain where the sensor data is combined:

Low-level fusion: In low-level fusion, the raw sensor data is combined into a common representation on which subsequent processing steps operate. For example, sensor data of multiple LIDAR can be combined into a common point cloud of increased angular resolution and vertical field of view (see Figure 4). Another common low-level fusion strategy is based on occupancy grid maps. The occupancy grid map (see Figure 5) is a discrete representation of the environment in which each cell contains the probability that a region in space is occupied by an obstacle. This probability can be computed based on the output of multiple sensors and sensor modalities [16].

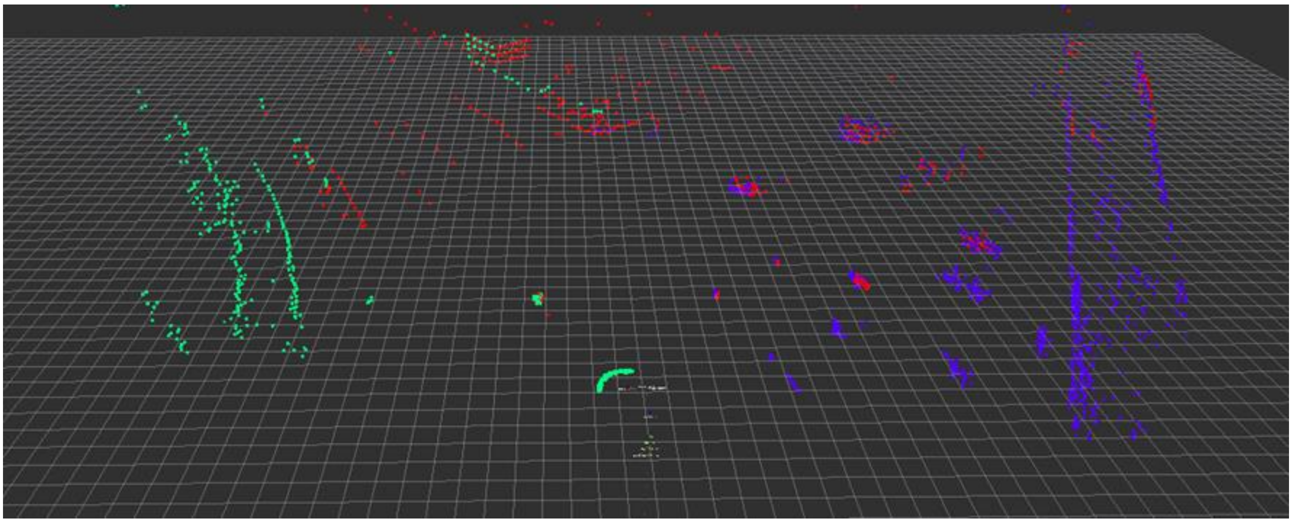


Figure 4. The sensor returns of three Ibeo LUX LIDAR (shown in green, red and blue) are registered into a common point cloud to increase vertical field of view and angular resolution. Further processing steps operate directly on the combined point cloud.

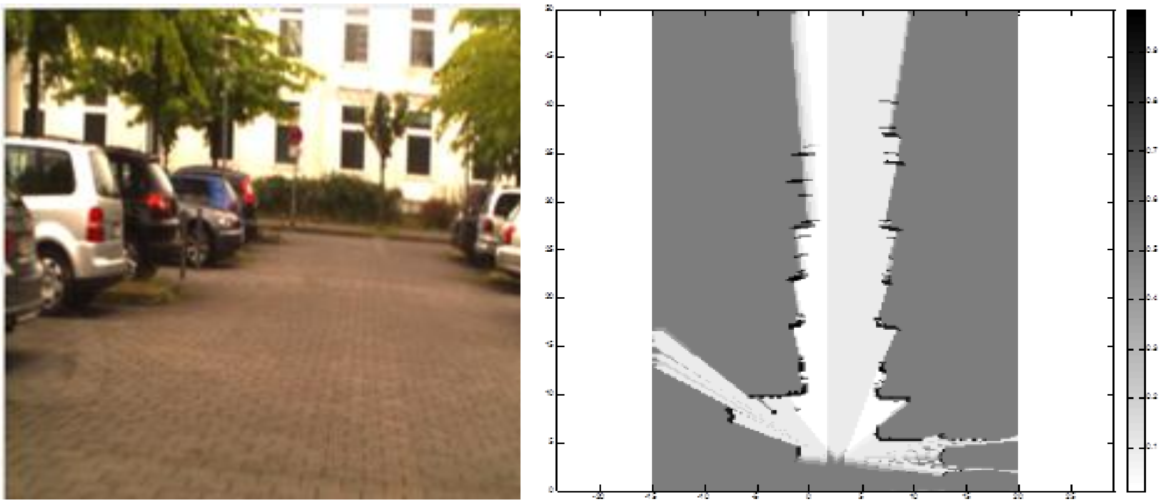


Figure 5. Left: camera image, right: corresponding occupancy grid map generated from LIDAR data.

Detection-level fusion: In detection level fusion, the raw sensor data is pre-processed to obtain detection responses from each of the available sensors, e.g. by thresholding the intensity of the returned signals. Then, the fusion algorithm combines these detections into a common representation. Two sources of uncertainty must be dealt with in detection-level fusion: sensor noise and unknown data association. Handling of sensor noise can often be solved optimally or nearly optimal in a recursive Bayesian filtering formulation using Kalman, particle or histogram filters [17]. Data association on the other hand is a much more challenging problem due to the combinatorial nature of the problem: if the identities of the objects which have generated the observed detections are unknown, the number of possible object trajectories grows exponentially with the number of detections and time steps. This makes multi-object (and multi-sensor) tracking an NP-hard problem.

Yet, principled approaches exist. For example, multiple hypothesis tracking enumerates all possible object trajectories and applies pruning strategies based on their likelihood in order to only follow the most probable hypotheses [18]. More recently, methods based on random finite sets [19][20] have become popular. These methods follow a rigorous mathematical treatment of recursive Bayesian filtering of set-valued phenomena.

Track-level fusion: In track-level fusion each sensor has its own processing pipeline to generate object hypotheses from raw sensor data. The generated tracks are then combined into a global representation using matching algorithms. Thus, compared to the detection-level fusion, in track-level fusion the matching is done at trajectory level [21]. An example of a track-level fusion architecture is shown in Figure 6.

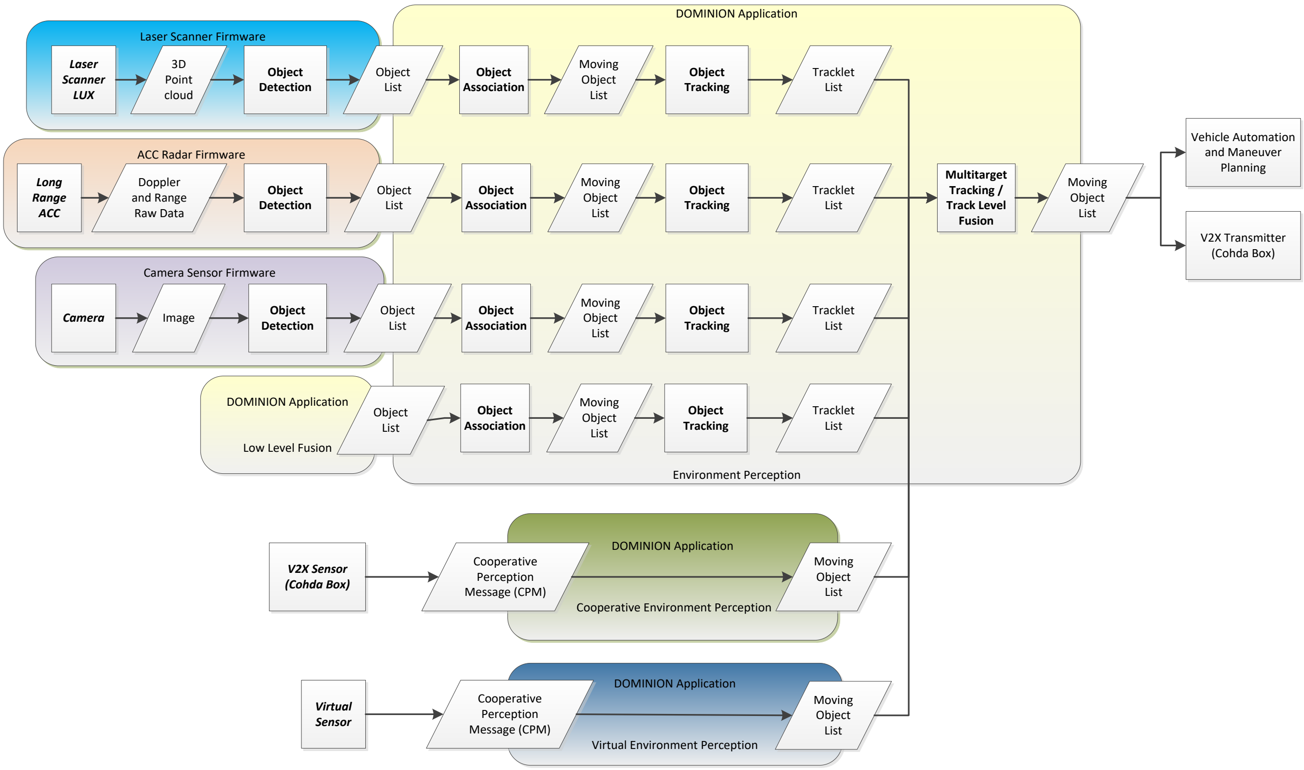


Figure 6. Track-level fusion building blocks. Each Sensor applies its own processing chain. The track-level fusion aggregates these object hypotheses into a common representation [22].

Generally, the less aggregated the data to be fused the bigger is the potential of data quality improvement by a good data fusion technique. The reason is that the later the stage, the higher is the level of data aggregation and the more data is lost before fusion. Further, compared to lower-level fusion, track-level fusion algorithms typically cannot provide guarantees such as Bayes optimality. However, depending on the application scenario, track-level fusion schemes may be advantageous over lower-level fusion because individual sensors operate separately, thus reducing the computational load at the fusion centre as well as the communication bandwidth.

2.1.1.3.2 Integration of CPMs into fusion architecture

The CPM definition imposes no requirements on real-time capabilities of the network transmission. Thus, messages may be received with a significant delay or even out-of-order. Further, the CPM contains processed sensor data on a per-sensor basis. As consequence, the data shared via CPM can only be integrated at the detection-level or track-level. A detection/track-level fusion scheme is therefore the most feasible approach.

Independent of the concrete system architecture, fusion systems typically apply probabilistic reasoning. In this regard, the CPM definition contains all relevant sources of uncertainties. Both, sensor and reference position and orientation are contained in the message definition. Based on this information, sensor output of one ITS-S can be incorporated into the system state of other ITS-Ss. Both fields have an uncertainty attached to them in form of a 95% error quantile with respect to the ITS-S coordinate system. Depending on actual sensor characteristics, these quantiles may represent a significant simplification compared to the true uncertainty representation. The 95% error quantile characterises a covariance matrix with only diagonal entries, thus capturing the variance along the coordinate axes of the reference system. If the actual sensor coordinate system is misaligned in rotation, the covariance in the reference system likely contains off-diagonal entries. Covariance is calculated by sensor measurement uncertainties (e.g. pixel, distance, or stereo triangulation uncertainty) plus systematic errors due to extrinsic sensor misalignment. For cameras with large uncertainty in depth, this may cause crude approximations.

Some sensors may not be able to measure all the fields in the CPM definition directly, in particular velocities and accelerations. While it is often possible to estimate corresponding values through Bayesian filtering, this must not hold for all sensor configurations. If “unknown” values are not allowed (as e.g. some parameters within the CPM are optional), such a case could be handled by setting the associated uncertainty to infinity or a numerical approximation.

Care should be taken with respect to which data is sent out by individual ITS-S. In order to prevent sensor data to be integrated multiple times into the fusion algorithm (this would lead to underestimated covariances), the sent data should not include information which was previously received from another ITS-S. Therefore, each ITS-S may only send the object hypotheses of its individual sensors, not the fused system representation that includes information from other ITS-Ss.

2.1.1.3.3 Sensor fusion at inductive loop infrastructure

Low-level fusion takes place at this type of infrastructure as well. As described in section 2.1.1.2.1 the inductive loop detectors analyse the vehicle signatures in more detail to draw conclusion about presence (profile value above threshold) and speed (comparing time difference of reference point on double loop).

More interesting is the fusion between different sensors, these can even be sensors of the same type. On intersections with an adaptive control algorithm, there is usually a “queue model” that models the arrivals upstream of the intersection towards the stop line and heuristics with loops on the stop line to conclude a vehicle has passed the stop line. The most challenging aspect is the estimation of the turning ratio’s, since upstream only a guess can be made whether the vehicle is turning right, straight or left. This means stop line detectors have to be monitored continuously to conclude which direction vehicles are going. An example of a queue model is shown in the figure below:

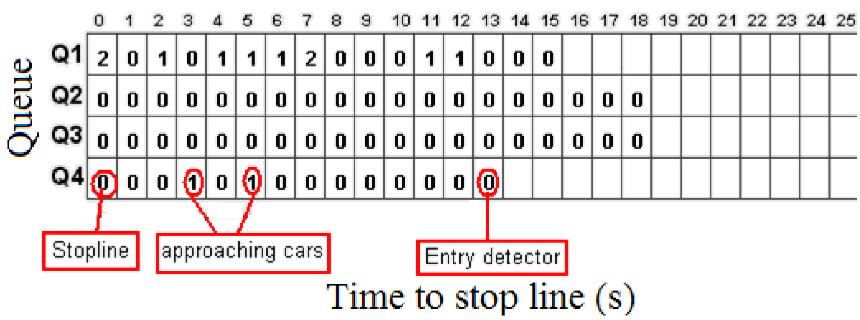


Figure 7. Example of shift-register as queue model.

Vehicles enter the model when they pass the entry detector and every second they are shifted one cell to the left, representing getting one second closer to arriving at the stopline. The leftmost cell represents the amount of vehicles waiting at the stop line. Once a vehicle passes the stop line, generally during a green phase, one vehicle is subtracted from this cell.

When two different sensor technologies are combined or C-ITS (Cooperative–ITS) messages are received, a different kind of fusion technique is required. For example, when a vehicle transmits a CAM message from which it can be concluded it is at a distance of 4 seconds to the stop line in Q4 in Figure 7, a fusion algorithm has to decide which vehicle in the queue model matches the CAM data. When a CAM is also sent with car following distance (see CAM extensions of the TransAID project at D 5.1 [4]), this will be easier, as there is no vehicle ahead of the vehicle in cell 3, while there is one vehicle ahead of the one in cell 5. In TransAID, these fusion algorithms had to be designed and implemented, especially for the motorway merging service, which requires accurate data of the approaching traffic. This is further described in section 2.2.1.1.1.

2.1.2 Existing studies on collective perception

Different studies have explored the potential of sharing sensor information for collective perception. For example, [23] and [24] were some of the first studies focused on analysing different sensing and fusion techniques. In these two studies, the raw sensed information was directly exchanged between vehicles. Alternatively, Kim *et al*. [11] investigated the exchange of raw sensor data, processed metadata (e.g. lane information represented in the point cloud) and compressed data (e.g. images from camera sensor) for collective perception. The results show that the communication delay increases with the amount of data transmitted so unnecessary data should be avoided.

To minimize the bandwidth required for collective perception and reduce the latency, [25] investigated the concept of sharing detected object data instead of raw sensor data. In this study, authors experimentally evaluate through field tests the transmission latency and range for different message sizes and rates. In addition, the study proposes a fusion architecture that includes a local fusion function (to process the ego-vehicle sensor data) and global fusion function (to processes the object data from different ITS stations) aimed at minimizing the amount of information to share.

Günther *et al*. [12] extended the message concept proposed in [25] for collective perception with different containers in order to specify the detected object parameters, sensor configurations and the characteristics of the transmitting vehicle. The receiving vehicle used this information to perform the coordinate transformation and to locate the detected objects. The efficiency of the proposed message is investigated with an obstacle avoidance scenario with two vehicles. The results show that the proposed solution allows vehicles to detect earlier a possible obstruction and hence improves the reaction time to handle a potential safety risk. The collective perception message concept proposed in [12] was evaluated under different low traffic densities in [26] and high traffic densities in [27]. Both studies considered different priority queues and Decentralized Congestion Control (DCC) mechanisms [28] with five different level of congestion states. Each state holds a specific packet transmission interval and the state transition is performed based on the measured Congestion Busy Ratio (CBR). In addition, two message variants were configured to share the collected perception information among V2X enabled vehicles. The first variant includes CAM and EPM (Extended Perceived Message) that are transmitted pairwise, and the second variant extends the CAM message by adding collective perception related data fields. These studies analyse the awareness ratio and channel load for scenarios with different CAVs market penetration rates. From the results, the authors conclude that the collective perception or cooperative sensing increases the awareness of the driving environment but could also increase the network congestion. Suggestions were made by the authors to incorporate collective perception information in the existing CAM [14] (an extended version) or move collective perception messages from the control channel (where CAM messages are transmitted) to a service channel [29].

Recently, the AutoNET2030 project [30] has developed a cooperative autonomous driving technology based on a decentralised decision-making system and incorporated cooperative perception as one amongst its major services to increase the perception range in the neighbouring cooperative vehicles. The project implements the cooperative perception primarily to focus on the lane change scenario to vigilantly handle the blind spots of the vehicles. For this purpose, the objects perceived over the vehicle sensors are transformed into an occupancy grid data using an occupancy grid algorithm and exchanged with the neighbouring vehicles. As the size of the occupancy grid data can rapidly grow based on the cell size, grid size and bits per cell, the exchanging content might exceed the packet's Maximum Transfer Unit (MTU) specified by the ETSI ITS-G5 standards. Hence, a real-time encoding and decoding algorithm is applied to the occupancy grid data to fit the information in one packet. AutoNET2030 proposes to exchange the occupancy grid data among ITS stations through a new message named Cooperative Sensing Message (CSM); the CSM is actually derived from extending the standard CAM message. AutoNET2030 also proposes to broadcast the CSM messages on a service channel to reduce the channel load of the control channel.

Fanaei *et al*. studied in [31] a transmission rate control mechanism for the collective perception and proposed an adaptive communication scheme for cooperative automated vehicles that dynamically controls the size/length and content of the messages based on the communication channel load. In the proposed system, the vehicles share a multi-resolution local map, which is derived from three distinctive sources that include the local sensing modalities, previous environmental knowledge and processing map data. While the local sensing modalities and the previous environmental knowledge are obtained from the vehicle itself, the latter is procured from the neighbouring vehicles. To have a reliable communication and to reduce the channel load, the proposed system adapts the size and content of the messages. On the one hand, the system adapts the size of the messages taking into account the CBR. On the other hand, the system adapts the content of the messages by identifying the potential known and the unknown objects that can be included in the message. Also, the system follows a hierarchical structure that includes all the potential unknown objects at the lowest resolution. Then the messages are filled by the inclusion of potential known objects. If any remaining space exists in the message, the resolution of the potential unknown objects is increased. The simulation-based study conducted in [31] shows that the proposed system is able to keep the Packet Error Rate (PER) below a defined threshold even with different densities of vehicles in the scenario. Gani *et al*. [32] extend the work presented in [31] and analyse the advantages of jointly controlling the transmission rate and length of cooperative sensing messages rather than controlling them separately.

The studies discussed so far focus mainly on V2V (Vehicle to Vehicle) communications. In [33], Wang *et al*. investigate collaborative sensing amongst vehicles assisted by the infrastructure and V2I (Vehicle to Infrastructure). In particular, [33] studies the possibility to utilize V2I to help relay data when V2V (based on mmWave) line-of-sight is not available. The obtained results show that V2I communications should be incorporated to support collective perception, especially at lower penetration rates of connected vehicles.

2.1.2.1 ETSI Collective Perception Service

ETSI TC ITS WG1 is currently working on the standardization of the Collective Perception Service (CPS) through the work items DTS/ITS-00167 and DTR/ITS-00183. The current developments are described in the Technical Report in [34] that will serve as a baseline for the specification of CPS in ETSI TS 103 324. The document reports the CPM format and its Data Elements, and the current CPM generation rules. In addition, the document discusses the use of message fragmentation and segmentation for large CPM messages, and the need to utilize multiple channels to avoid saturating the control channel. As the ETSI CPS standardization process is still ongoing, this section depicts the main ideas that are being outlined in the CPS drafting sessions and what to expect. However, all the information provided in this document regarding the ETSI CPS is preliminary and might be subject to alteration in the final version of the Technical Report.

2.1.2.1.1 Data Format Specification

The selection of a data format is essential to achieve reliability and efficiency in the CPS. Sharing raw sensor information is a simpler and straightforward approach but can create compatibility problems when shared among different technologies or vendor providers. In addition, sharing raw sensor data consumes much higher channel bandwidth due to the large data size. To address these issues, the ETSI's CPS considers sharing the sensed information in a common/standard format using abstract (enumerated) object descriptions. The object description also includes information about the object dynamic state, geometric dimensions and time references. This common/standard format seeks eliminating compatibility issues. It also enables the classification of objects and the establishment of priorities and therefore the possibility to filter out objects that are redundant or unnecessary.

A key process to enable the object identification and classification is the feature extraction (e.g. edge detection). However, the mechanisms and technology involved in the sensor data's feature extraction is not discussed in the Technical Report, as it is considered beyond the scope of ETSI's CPS standard. Another important aspect of the format specification is the decision on whether to share individual objects detected by each sensor or to fuse the sensor data and share common objects at once. The former will avoid further processing delays, but it will incur a higher channel utilization due to the redundancy in the transmission of the same object detected by different sensors. The latter contrarily performs the fusion operation and derives a single object description for the detected object with the cost of higher computational complexity and delay.

Further, the sensor fusion process itself can be performed either at low-level or high-level. In low-level object fusion process, the raw sensor data from multiple sensors are fused directly. In high-level object fusion process, the raw sensor data is processed individually, and the obtained object data is later fused based on the ITS-S manufacturer specifications. The Technical Report has preferred low-level fusion process over high-level fusion process. As different manufacturers may have different fusion specifications, the higher-level fused object dynamics may be error-prone. For example, the obtained objects may differ in the two-dimensional spatial information which may affect the coordination process at the receiver node.

The processing of the detected objects at the receiver side also influences the data format. For example, the dynamics of the detected objects are derived at the receiver side based on the local coordinates of the originator stations. This demands a coordinate transformation process to be integrated at the receiver side to map the received object descriptions onto its local coordinates system. To make the local coordinates of the originator stations available at the receiver node, they need to be added in the message. Additionally, to increase the consciousness of the detected object descriptions at the receiver node, information about the sensors utilized by the originator station and their capabilities is also integrated in the message.

2.1.2.1.2 Message Format

The current structure of the CPM includes an ITS PDU (Packet Data Unit) header and 4 types of containers (as shown in Figure 8): a Management Container, a Station Data Container (these two containers form the Originator Station Container (OSC)), one or more Sensor Information Containers (SIC), and one or more Perceived Object Containers (POCs) [34]. The ITS PDU header was specified in [35] and includes Data Elements (DE) such as the protocol version, the message ID and the station ID. The Management Container (MC) is mandatory in the CPM and provides basic information about the originator station including its position and type. The Station Data Container (SDC) is optional and includes additional information about the originator. It differentiates the originator vehicle and RSU and specify its additional properties. The Sensor Information Container is optional and includes details about the sensor properties. The Perceived Object Container is optional and specifies the dynamic state and properties of a detected object(s).

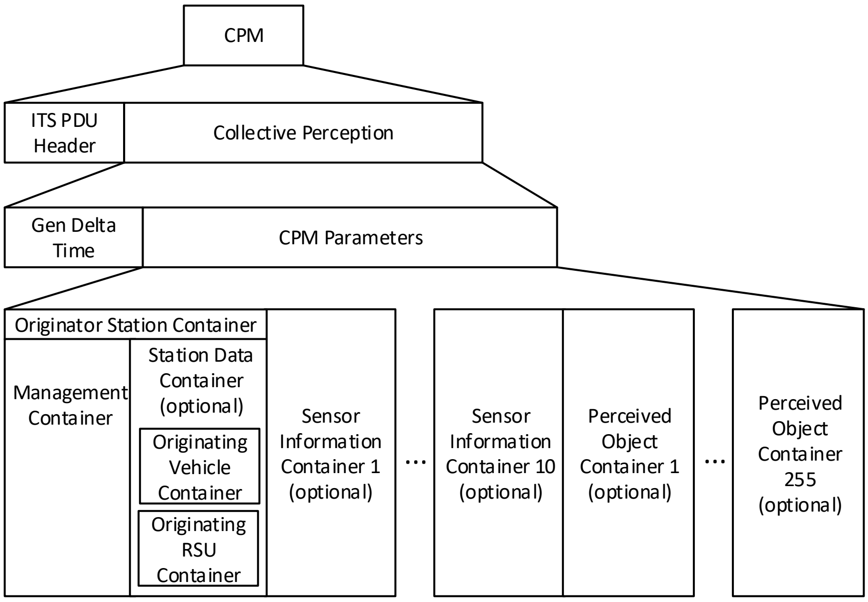


Figure 8. CPM General Structure (ETSI TR 103 562-v0.0.15)

2.1.2.1.2.1 Originating Station Container

The OSC includes properties and specifications about the originating ITS station that is required at the receiver ITS station to perform the necessary sensor data fusion and the coordinate transformation process. The OSC contains an MC and an SDC container. The MC contains information about the originator ITS station reference position and provides the horizontal position accuracy with a predefined confidence level. It also contains the Station Type that informs about the type of the originator ITS station as specified in [35] and that can be a vehicle or a RSU. The MC also includes the Action ID that is used to identify a set of objects distributed in consecutive CPMs and enables to track the objects in space and time.

Since both the vehicle and RSU ITS stations can generate the CPM, the SDC is defined as a choice between the Originator Vehicle Container (OVC) and Originating RSU Container (ORC). In case of vehicle ITS stations, the OVC contains mandatory and optional Data Fields (DFs) to describe the attributes of the vehicle dynamics such as heading, speed, angle and many more. In case of RSU ITS stations, the ORC has the choice between two DF parameters: Intersection Reference ID or Road Segment ID. These DF parameters are derived from the existing MAPEM (MAP (topology) Extended Message) [36]. These parameters are useful for the receiver ITS stations to match the received object dynamics to the geometric boundary of the defined intersection or road segment.

2.1.2.1.2.2 Sensor Information Container

The SIC describes the sensing capabilities of the originator ITS station. The SIC is used by the receiving ITS stations to derive the areas that are currently sensed by the originator ITS stations. A SIC includes the ID of a sensor, its type (e.g. RADAR, LIDAR or a sensor fusion system) and its detection area, among other Data Elements. It also specifies whether the sensing capabilities of the originator ITS station are from separate sensors or collectively from the sensor fusion. In the first case, the SIC is recurrent for each sensor type and its sensing capabilities are reported individually. In total, a maximum of ten unambiguous SIC can be added in the CPM to report individual sensor properties. In case of sensor fusion, a single SIC is incorporated in the CPM and the general sensing capabilities of the collaborative sensors are reported.

The Data Fields included in the SIC are differentiated by two attributes namely Sensor Entry and Sensor Details (Table 1). The Sensor Entry is common includes the Sensor ID that defines a unique identifier, and the Sensor Type defines the type of sensor or the fused information. The Sensor Details subfield has a choice between defining the sensor properties of the vehicle (Vehicle Sensor) or RSU stations (Station Sensor Radial). These DFs specify the sensor measurement regions through defining sensor mounting position, sensor range and sensor opening angle. Other optional DFs in the SIC are the Stationary Sensor Polygon, Stationary Sensor Circular, Stationary Sensor Ellipse or Stationary Sensor Rectangle that specify the position and respective regions of sensors for objects detection. These optional DFs are particularly useful when several separate sensors are combined and projected as a single sensor module.

Table 1. Sensor Information Container (ETSI TR 103 562-v0.0.15)

Container			Data Fields (DF) / Data Elements (DE)
Sensor Information Container (SIC)*	Sensor Entry		Sensor ID
			Sensor Type*
		Sensor Details‡	Vehicle Sensor
			Stationary Sensor Radial
			Stationary Sensor Polygon
			Stationary Sensor Circular
			Stationary Sensor Ellipse
			Stationary Sensor Rectangle

* Optional ‡ Choice

2.1.2.1.2.3 Perceived Object Container

The POC is optional and describes the dynamic state and properties of the detected objects (Table 2). This container includes the sequence of Object Data elements that includes various mandatory and optional fields to describe the abstract dynamic properties of the individual detected object. A new POC is added for every detected object and a maximum of 255 POC containers can be added in the CPM. The Object ID DF in the POC provides an identifier for the individual detected object that can be used for tracking purposes. The Sensor ID DF in the POC specifies the corresponding sensor information that detects the object. Other mandatory DFs such as the Time of Measurement and Distance provide the state and space information of the detected objects with respect to the originator station reference point. The receiver is responsible to perform the process to transform the detected object dynamics with respect to its reference points. To classify the type of the detected object, a Classification mandatory DF is added in the POC container. Several optional DFs like Object Age, Object Confidence, Speed, Acceleration, Yaw Angle, Dimensions, Dynamic Status and

Matched Position will provide a more detailed description of the detected object and enable the receiver to coordinate and track the detected object in a three-dimensional space.

Table 2. Perceived Object Container (ETSI TR 103 562-v0.0.15)

Container		Data Fields (DF) / Data Elements (DE)
Perceived Object Container (POC)*	Object Data	Object ID
		Sensor ID
		Time of Measurement
		Object Age*
		Object Confidence*
		Distance
		Speed*
		Acceleration*
		Yaw Angle*
		Planar Object Dimension*
		Vertical Object Dimension*
		Object Ref Point*
		Dynamic Status*
		Classification

*Optional

2.1.2.1.3 Message Triggering Conditions

The CPM generation rules define how often a CPM is generated by the originator station and which information (detected objects and sensors information) is included in the CPM. Periodic and dynamic policies are being investigated and discussed as part of the ETSI standardization process.

The periodic policy generates CPMs periodically every *T_GenCpm*. In every CPM, the originator station includes information about all the objects it has detected. The CPM should be transmitted even if no objects are detected. The periodic policy is being used as a baseline in the standardization process to compare its performance and efficiency with more advanced policies such as the dynamic one. With the dynamic policy, the originator station checks every *T_GenCpm* if the environment has changed and it is necessary to generate and transmit a new CPM. If it is, the vehicle also decides the objects that should be included in the CPM. A vehicle generates a new CPM if it has detected a new object, or any of the following conditions are satisfied for any of the previously detected objects:

a) Its absolute position has changed by more than 4m since the last time it was included in a CPM.

b) Its absolute speed has changed by more than 0.5m/s since the last time it was included in a CPM.

c) The last time the object was included in a CPM was 1 second ago.

All new detected objects and those that satisfy at least one of the previous conditions are included in the CPM. If no object satisfies the previous conditions, a CPM is still generated every second, but only including the Management Container, the Station Data Container and the Sensor Information Containers (i.e. without any Perceived Object Container). It should be noted that these CPM generation rules are an adaptation of the CAM generation rules [14] for detected objects. In addition, these generation rules are preliminary and only a first proposal (hence subject to possible changes in the final specifications) that must be now carefully analysed to understand its road traffic and communication implications.

2.2 First Iteration

2.2.1 TransAID Sensor Fusion

This section discusses the approach chosen in TransAID for the sensor fusion. Separate subsections discuss the road infrastructure at motorways with C-ITS data, camera sensor fusion and vehicle sensor fusion.

2.2.1.1 Sensor fusion at the infrastructure

2.2.1.1.1 Sensor fusion for motorway approach models

The merging assistant service in TransAID requires an accurate model of a section of approximately 1500m of motorway. This is demonstrated in Figure 9, which is taken from the TransAID Service 2 described in D4.1.

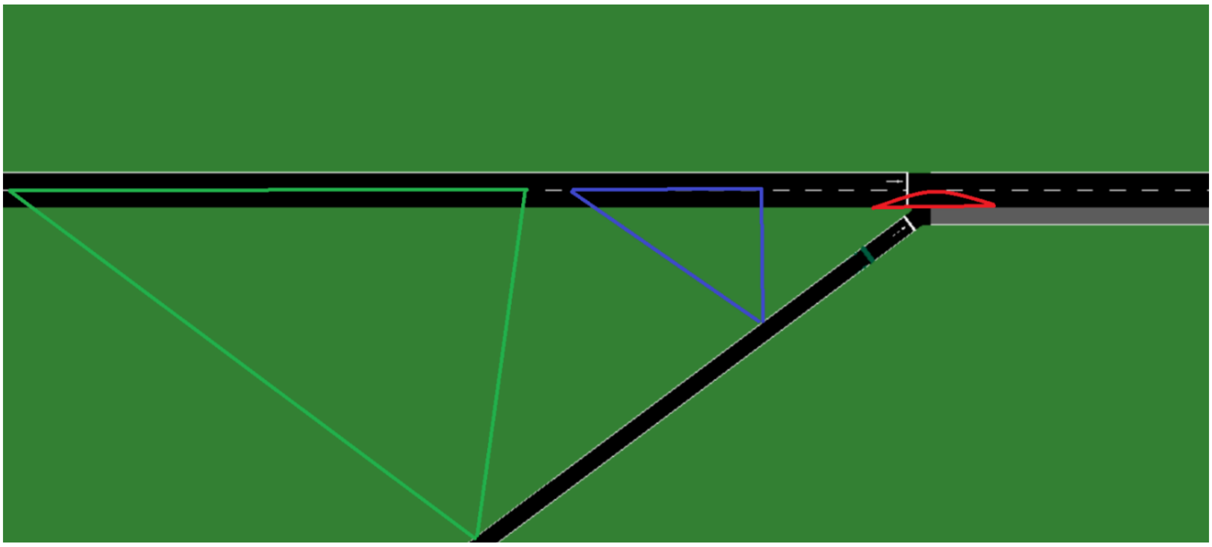


Figure 9. Detection area for gap selection for AV (red), LV (blue) and infrastructure assisted C(A)V (green).

New vehicles entering the motorway onramp get a gap assigned in the green area, which is a much bigger range than the red for CAVs without infrastructure assistance, or the blue estimate of what human drivers can oversee in LVs. After the gap selection, the vehicles keep being monitored to further guide onramp vehicles up to the merging area when they have changed lanes.

The model designed to support the merging assistant takes three data inputs and fuses them according to a certain hierarchy. This is illustrated in Figure 10:

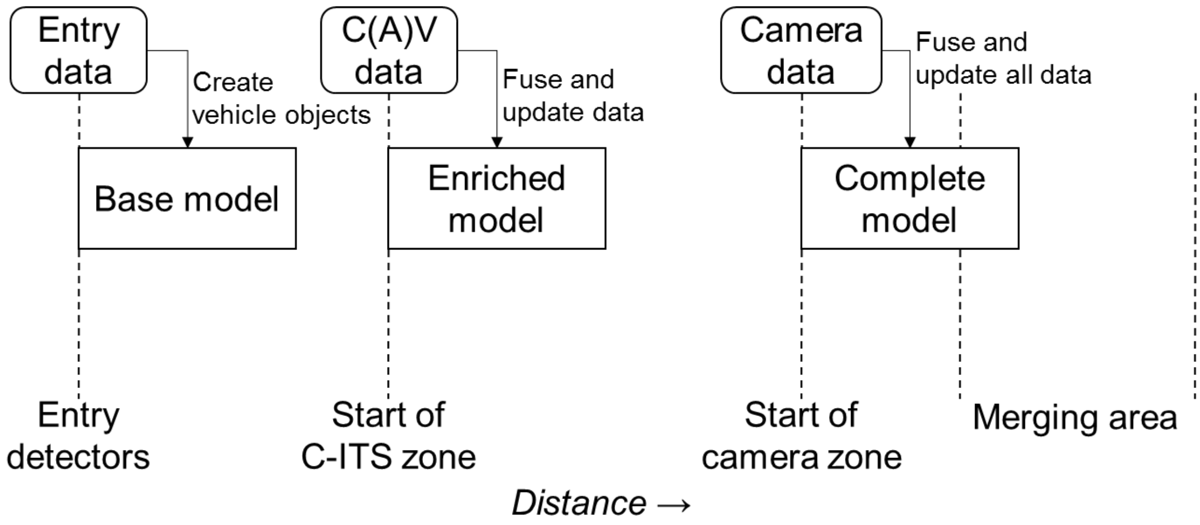


Figure 10. Traffic model for merging assistant.

The model starts with data from traditional sensors that can measure speed and occupancy. These are marked as "entry detectors" in the diagram and are usually traditional loop detectors that can only measure presence. Because they are double loop detectors at a small known distance, the speed can also be measured. Once a vehicle leaves such a sensor, it is processed as an entry for the model. Then every time step the vehicle is moved closer to the merging area according to its speed, keeping constraints of minimum following distance into account. This results in the base model in the figure.

A major problem with this base model is that the speed is assumed constant, while in reality especially human drivers vary their speed. Therefore, once C(A)Vs get in range of the RSU and CAM messages with speed and position data are received, corrections can be made to the model. The position of the C(A)V is compared to the positions of the vehicles in the base model and the closest is selected and subsequently flagged as C(A)V for future data fusion purposes. This is illustrated in Figure 11 below:

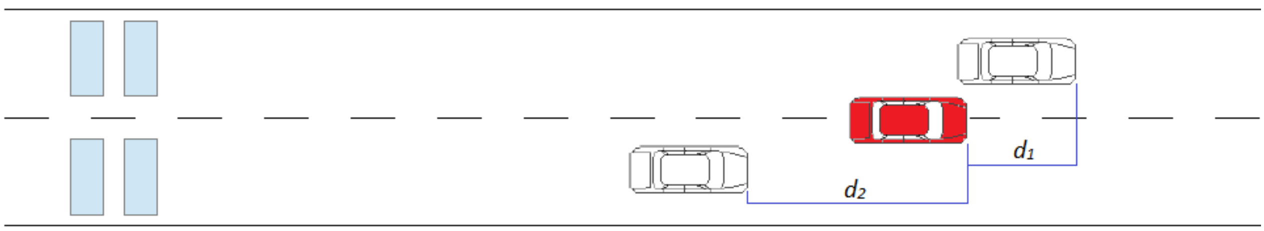


Figure 11. Data fusion of CAM with base model.

For example, when the base model indicates there is one vehicle at 500m from the merging area and one at 520m and a cooperative vehicle is detected at 505m, then the distance to the first vehicle, d_1, is 5m while d_2 is 15m and it is likely the first vehicle is the C(A)V of which data is received. The data fusion also needs to define a maximum deviation before a new vehicle is created. Loop detectors have an accuracy of around 95-99%, depending on the maintenance state, so detections can be missed. Therefore, if there are no vehicles within the error margin, an extra vehicle will be created in the base model with the cooperative flag set. This flag is essential for future updates of the CAM message, because it links to the *stationID* and the model doesn't need to find the vehicle every time a message is received. This results in frequent updates to the speed and position for CVs. A problem is that CVs don't indicate their current lane, which reduces the accuracy of the fusing algorithm. This is why the red measured vehicle in the figure is not yet placed in one of the lanes. Speed can also be a factor for the selection as it is unlikely for a fast vehicle to be on the outer lane when there are slower trucks in the model at that position. With more than two lanes, however, this becomes significantly harder. For CAVs, the current lane and the distance to the surrounding vehicles can also be updated. This makes data fusion easier and the relative distance to other vehicles is interesting to acquire data about unequipped LVs around. These concepts together result in the enriched model of the figure.

As a last step, a tracking sensor is used to monitor the situation close to the merging area. This sensor has speed, position and current lane information for all vehicles, which will therefore give a complete model. This sensor is, however, expensive to install and maintain, so it is only used in the area where it is really necessary. With higher penetration rates of C(A)Vs the sensor is probably not required anymore. Data fusion of this sensor with the other data is implemented with the same principles. CVs with uncertainty of their current lane can be matched exactly according to their position, while LVs follow the principles of selecting the closest in the model, or creating a new vehicle. Lastly, this model also enables removing of LVs that were expected to be around, but are not there anymore. Vehicles will be held at the edge of the detection zone for a few seconds before being removed from the model.

This concept is further demonstrated in Figure 12. At t = 0 a new vehicle is detected by the tracking camera at the left lane. At that moment, another vehicle was close to it, so this was easy to fuse. At t = 1, a vehicle on the right lane reaches the monitored area, but the tracking camera does not see it yet. Therefore, until t = 3, the vehicle is held there in the model. The vehicle behind it, is also held, but at a larger distance to keep realistic and safe car following distances in the base model. At t = 4 (not in the figure) the 2^{nd} vehicle would have reached the monitored area and at the same time the other vehicle timed out and is removed. At t = 7, (last situation in the figure), the tracking camera detects a vehicle on the right lane, which is fused with the only remaining vehicle that was held at the edge of the monitored area.

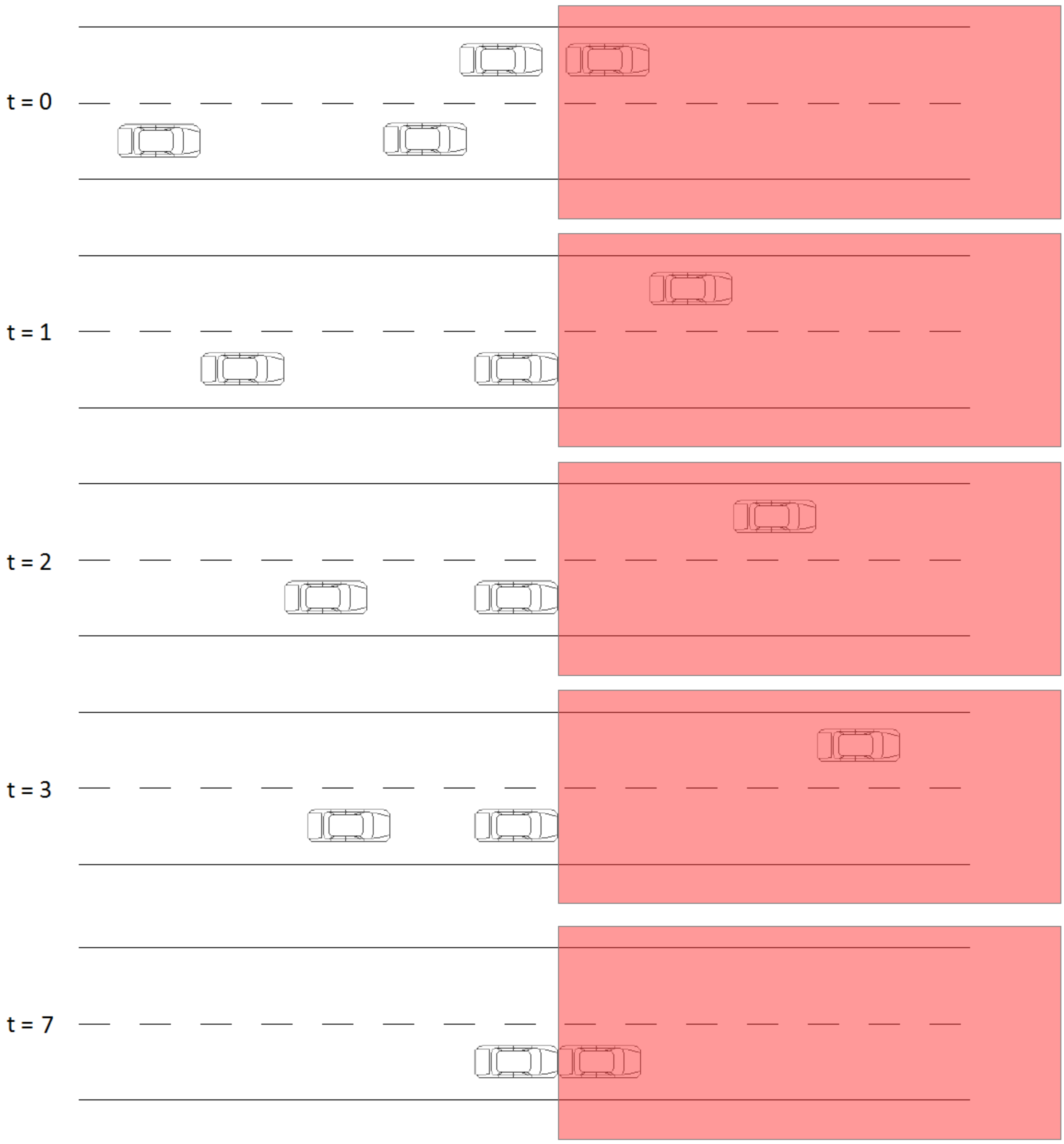


Figure 12. Data fusion concepts with tracking camera.

2.2.1.1.2 Enabling sensor fusion with road-side camera infrastructure

The camera RSU generates object trajectories from video sequences, converts them into station-relative 3D coordinates and generates CPM to publish them via V2X. As illustrated in Figure 13, input is a sequence of camera images which are real-time processed by object detection and tracking modules. First, the *object detection* module generates hypotheses about objects as cars, cyclists, or pedestrians being denoted as bounding box with confidence value in the image frame. The following module *optical flow* estimates image feature point trajectories describing the visual movement characteristics of visually trackable (i.e. textured and identifiable) image regions around these points. Together with the object bounding boxes, the *object tracking* module combines them into object trajectories, which means unique (re-)identification of objects over time and the estimation of their trajectories in the image frame. Finally, the *back-projection* module generates metric and scaled 3D object trajectories relative to the RSU. For this, intrinsic and extrinsic camera calibration is required. Based on this 3D object data, the *V2X communication interface* is used to generate and transmit e.g. CPM.

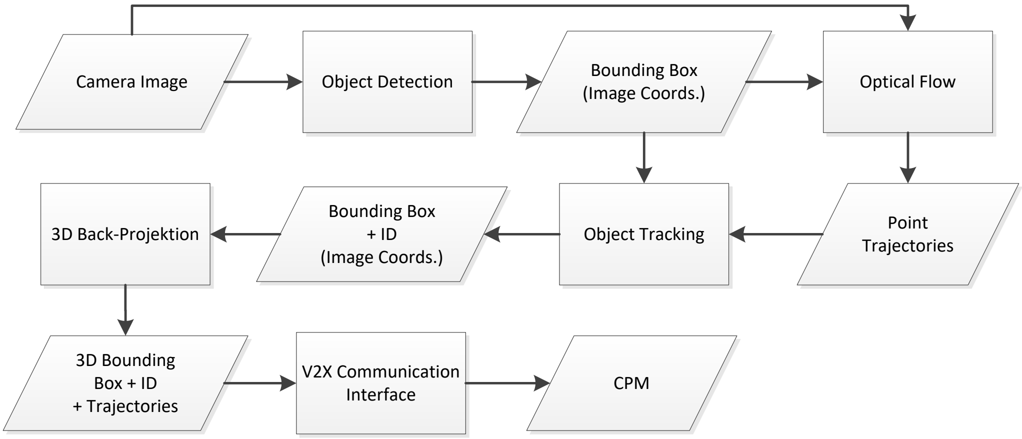


Figure 13. Overview of the infrastructure-based software components.

A visualization of the output is shown in Figure 14. The image shows object detection together with color-coded unique identifiers that will remain over time for each object. With the usage of optical flow measurements and subsequently the prediction of visual movements, detection errors can be compensated. For example, the cyclists in the lower right image region (IDs 47, 145, 177) are successfully tracked also on partly occlusions while they are moving behind/next to a queue of driving and parked cars.

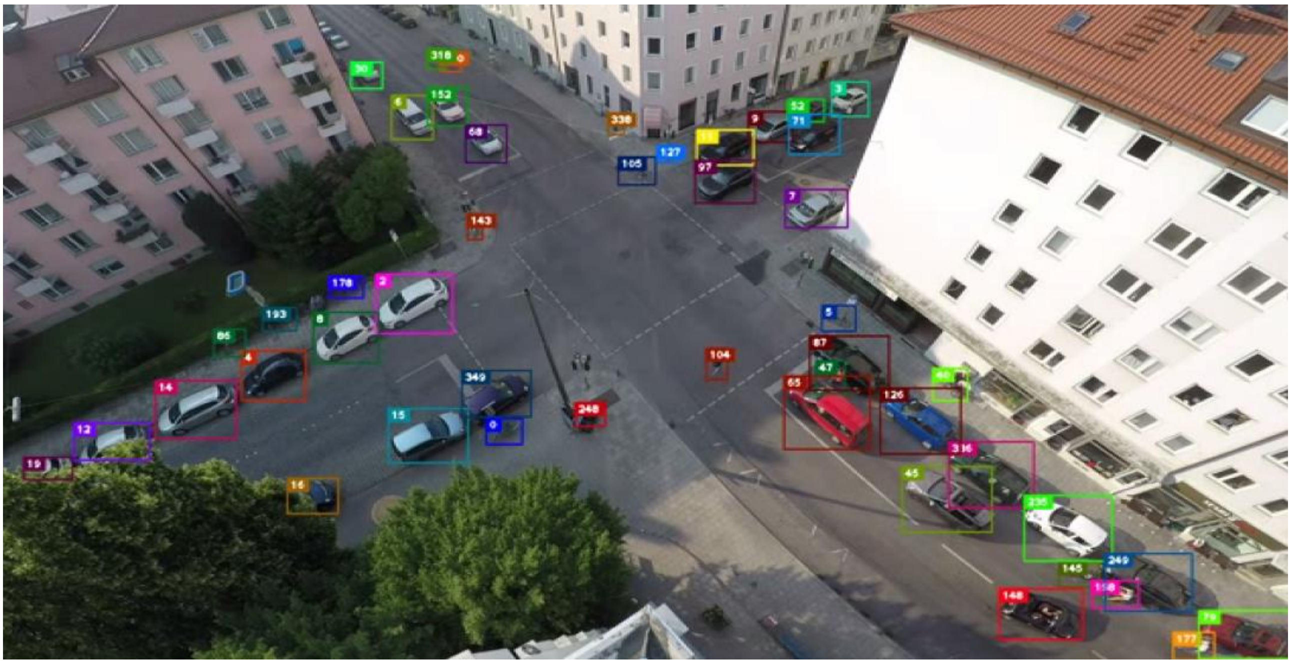


Figure 14. Road intersection scene with identified and tracked objects overlay.

2.2.1.1.2.1 Object detection

Current state-of-the-art methods are based on Convolutional Neural Networks (CNNs) [37]. Within the overall system, a software module was integrated which uses CNNs by using the TensorFlow Object Detection API [38]. This library is a widely used deep learning framework, and the pre-trained models provided are within a wide spectrum between efficiency and accuracy. Figure 15 shows the output of two CNNs of different complexity. In the upper image, a rather small *MobileNetV1* with a run time of 56 ms (for this image) is used. The lower image shows the output of *ResNet 101* with a run time of 106 ms. The latter network is slower but can detect all the objects.

Figure 15. CNN-based detection result with backbone *MobileNetV1* (upper image) and with backbone *ResNet 101* (lower image). Image source: KITTI dataset [39].

2.2.1.1.2.2 Optical flow

This module generates feature point trajectories over the image sequence. The implemented method is based on the feature detector FAST [40] which is applied on every image. For every significant image point (i.e. with re-identifiable region around the coordinate), the trajectory is tracked, or a new trajectory is initialized if the feature point is new. Features too close to existing trajectories are suppressed to limit its number. Additionally, feature identification can be limited to image regions of interest, i.e. where object hypotheses exist. This leads to further reduction of computation time. Optical flow, i.e. tracking from image to image is computed with the fast Lucas-Kanade method [41] or with dense optical flow [42]. In both cases, optical flow vectors are validated by backwards tracking. If tracking becomes unconfident, the feature point trajectory is terminated.

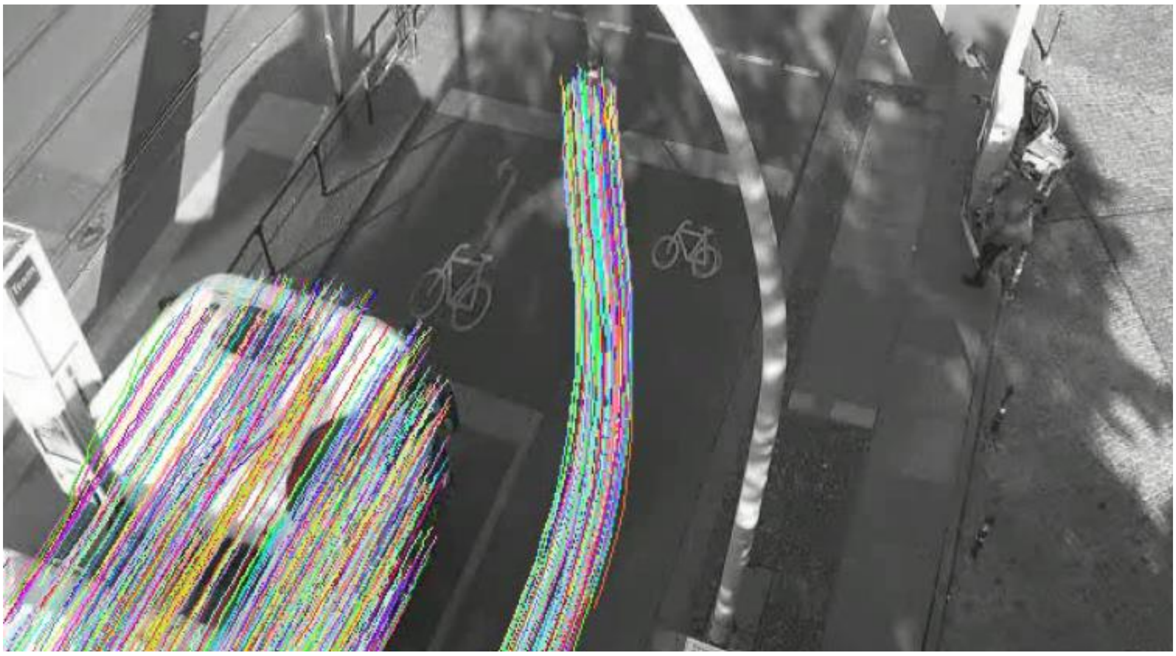


Figure 16. Color-coded visualization of feature point trajectories of a truck and a cyclist.

2.2.1.1.2.3 Object tracking

Goal of this module is the estimation of object correspondences over time and the generation of unique identifiers for every object such that the single-image-based detections can be combined to trajectories over time. The task is modelled as optimization problem [43] which is illustrated in Figure 17. For a given input sequence, a graph is created where each detected object corresponds with a node. A source (s) and sink (t) is added which correspond to start and end of each trajectory. Thus, every s-t-path is one possible object trajectory. Since the number of objects is usually unknown, the solution of this object tracking problem is the set of non-overlapping s-t-paths with minimal cost. The constraint that the s-t-paths must not overlap ensures that each object is given maximally one identity.

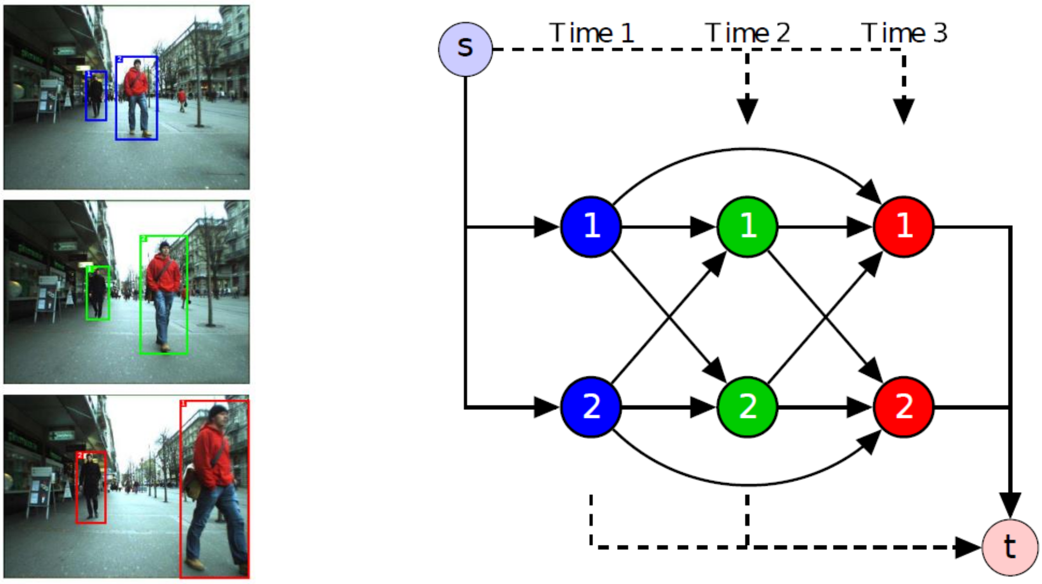


Figure 17. Illustration of a network flow graph over a sequence of three images (i.e. timestamps) with two detected objects. For every object, a node is added to the graph. Edges between nodes are possible object transitions between the images.

The goal is now to find an optimal solution with minimal cost. Such minimal-cost problems can be exactly solved in polynomial time. For the existing graph structure (no loops, edges with all the same direction), fast methods are existing that can solve the problem in linear time depending on the length of the image sequence [44]. The performance is mainly depending on the quality of input data (i.e. true positive object detection) and the precision of the cost function within the optimization. Figure 18 shows two detections of the same person in different images and illustrates how the transition cost can be calculated depending on the point trajectories from optical flow estimation. With the assumption that object detections from different images do likely refer to the same physical object if many feature point trajectories are within both object boundaries, the (inverse) cost is modelled as the amount of feature points that lie in the same corresponding object bounding box.

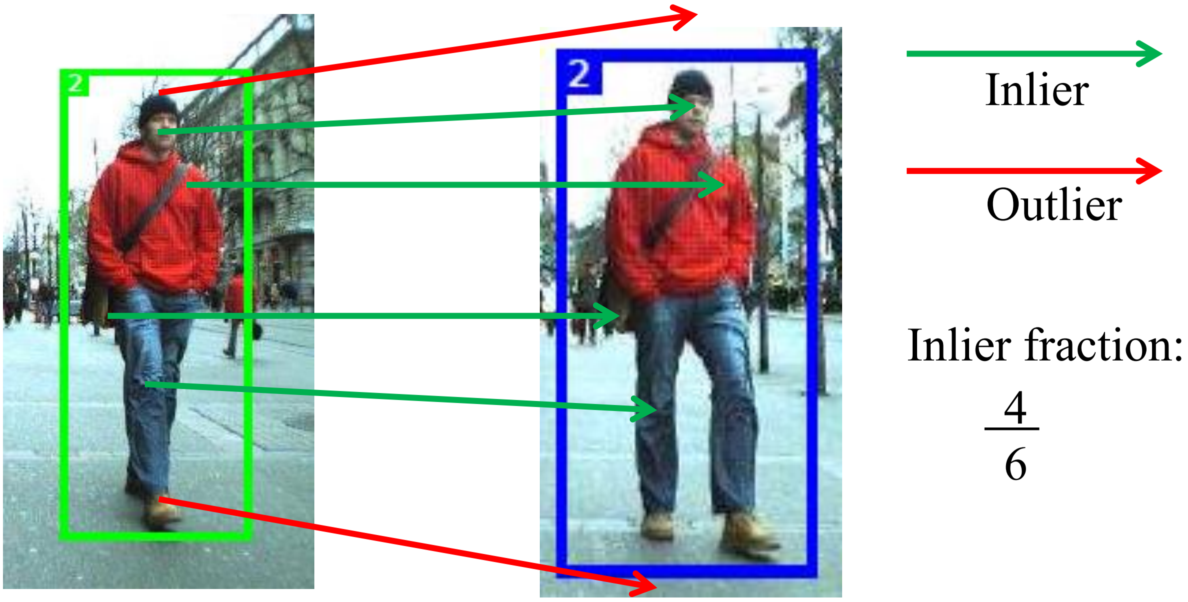


Figure 18. Calculation of movement cost terms. Object bounding boxes do probably refer to the same person if many optical flow vectors (i.e. visible movements in the image frame, marked as arrows) begin in one box and end in the other.

2.2.1.2 Sensor fusion at the vehicle

The TransAID project employs a hybrid sensor fusion strategy which contains a low-level LIDAR fusion module and an object-level fusion module. The low-level fusion module transforms the sensor data of multiple laser scanners into a common coordinate system. The object-level fusion module fuses in-vehicle sensor data with collaborative perception data from V2X messages. An overview of the processing pipeline is shown in Figure 19. In the following, we give a brief description of the processing modules in this figure.

Low-level Data Fusion The vehicle has multiple laser range finders (mounted at t front and rear). The data acquired from these sensors is transformed into a common sensor coordinate representation within the low-level data fusion module. This transformation is performed based on extrinsic calibration (sensor position and orientation) which is available through a scene graph representation of the entire vehicle setup. The low-level data fusion module is also responsible to filter ground readings from obstacle readings. Ground readings are dropped from the point cloud as they impose no threat to vehicle automation.

Background Subtraction The registered obstacle point cloud is passed from the low-level data fusion module to a background subtraction module. This module identifies dynamic from static obstacles via scan matching: At each time step, the current point cloud is registered against a local map constructed from point clouds obtained at the previous time steps using a variant of the Iterative Closest Point algorithm [45] with initial guess taken from the ego-localization provided by a real-time kinematics device. Based on a configurable minimum object velocity, point correspondences between the map and the current scan are established using nearest neighbour search. Using this procedure, points with correspondence in the map are marked static and points without correspondence are marked dynamic.

Clustering & Tracking The clustering and tracking module partitions the cloud of dynamic points into clusters. In order to estimate object velocities, these point clusters are tracked over time using a Kalman filter. The final object hypotheses are formed by fitting an oriented bounding box to the raw point data.

Object-level Fusion The object level fusion module takes tracks from multiple sensor sources to construct a global track set. At this stage, objects from the in-vehicle sensor are fused with objects of other vehicles transmitted via V2X perception messages. The TransAID project is implementing a method based on [46] to establish track-to-track correspondences using a greedy local search. Object-level fusion operates at a fixed update rate, which can be different from the update frequency of different sensors. However, as individual sensor sources transmit full kinematic states (position, velocity, acceleration) rather than raw sensor data, trajectories of individual sensors can be interpolated or extrapolated to deal with asynchronous update frequencies.

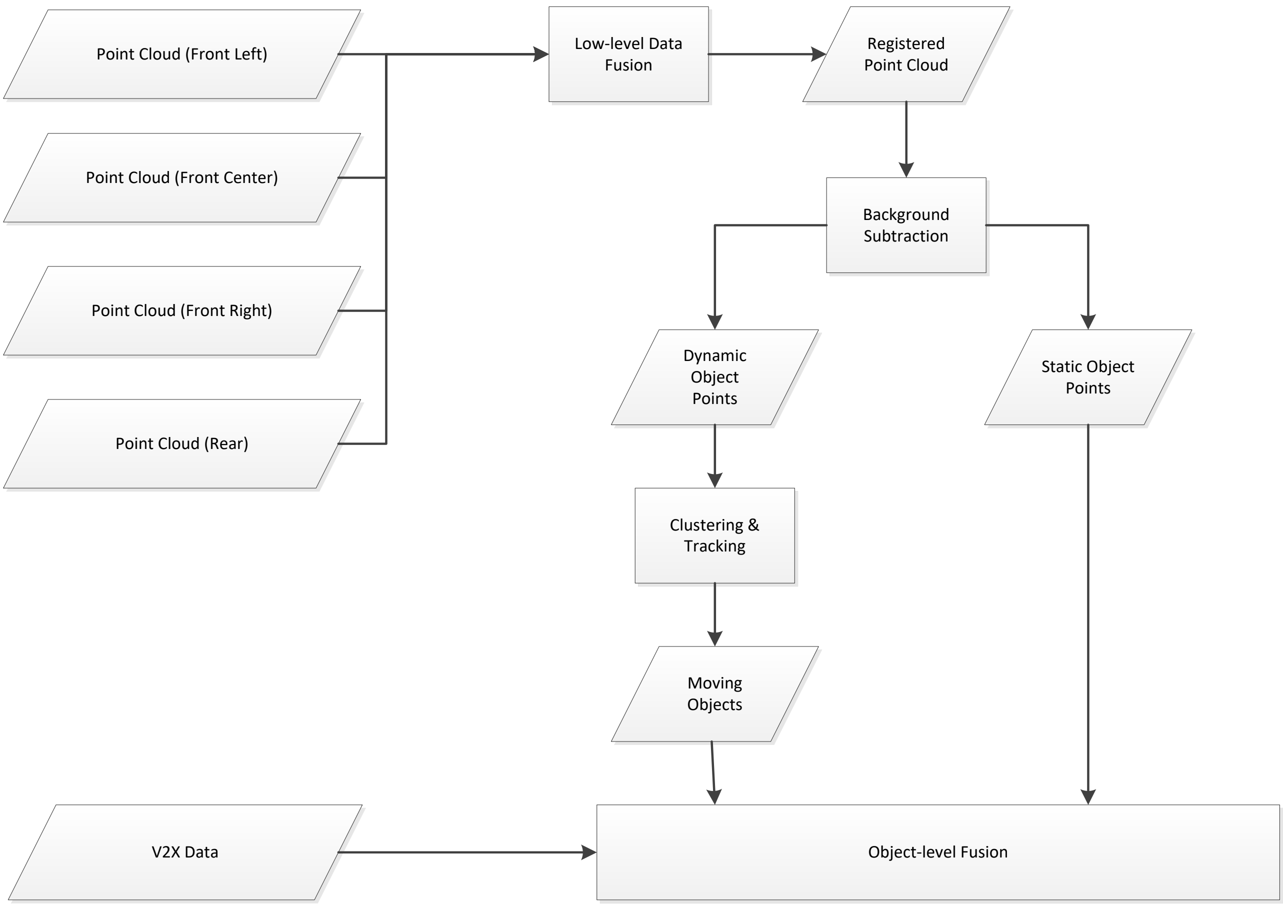


Figure 19. Overview of the TransAID project vehicle sensor fusion architecture.

2.2.2 Performance evaluation of ETSI Collective Perception

As part of the work that is being conducted in TransAID to contribute to the ETSI's CPS (see Annex A), this section shows an in-depth evaluation of the operation, communications performance and perception capabilities of the different collective perception message generation rules proposed in the ETSI CPS standardization [34] through simulations using NS-3. We have extended the NS-3 with a CPS component and different on-board sensors. The CPS component implements the periodic and the dynamic CPM generation rules. Two different periodic policies with 10Hz (*T_GenCpm*=0.1s) and 2Hz (*T_GenCpm*=0.5s) have been considered as a baseline in this study. In the dynamic policy, the *T_GenCpm* parameter has been set to 0.1s, so that the maximum CPM rate is 10Hz. The CPM size is dynamically calculated by the transmitting vehicle based on the number of containers in each CPM. The size of each container has been estimated offline using the current ASN.1 definition of the CPM [34]. To this aim, we have generated 10^4 standard-compliant CPMs. Table 3 reports the average size of the containers that are used in this study. In our scenario, each vehicle is equipped with two on-board sensors looking forward [34]. Sensor 1 has 65m range and a field of view of ±40 degrees. Sensor 2 has 150m range and a field of view of ±5 degrees. The sensor shadowing effect (sensor masking) is implemented in the XY-plane, and we assume that the sensors can detect only the vehicles that are in their Line-of-Sight (LoS) [33]. We assume that the objects detected by the two sensors are fused.

Table 3. CPM Containers

CPM Container	Size
ITS PDU header Management Container Station Data Container	121 Bytes
Sensor Information Container	35 Bytes
Perceived Object Container	35 Bytes

The traffic scenario is a six-lane highway with 5km length and a lane width of 4 meters. We simulate two different traffic densities following the 3GPP guidelines for V2X simulations [47]. The high traffic density scenario (120veh/km) has a maximum speed of 70km/h, while the lower one (60veh/km) has a speed limit of 140km/h. For each traffic density, this study considers different speeds per lane. The speeds have been selected based on statistics of a typical 3-lane US highway obtained from the PeMS database [48]. We analysed the lanes speed of the highway for every hour within a single day and took the average speed for each individual lane. Vehicles created in the simulations have the dimension of 4.8m x 1.8m [33]. To avoid boundary effects, statistics are only taken from the vehicles located in the 2km around the centre of the simulation scenario. The configuration of the scenario is summarized in Table 4.

Table 4. Scenario parameters

Parameter	Values	
	Low traffic density	High traffic density
Highway length	5km	
Number of lanes	6 (3 per driving direction)	
Traffic density	60 veh/km	120 veh/km
Speed per lane	140 km/h 132 km/h 118 km/h	70 km/h 66 km/h 59 km/h

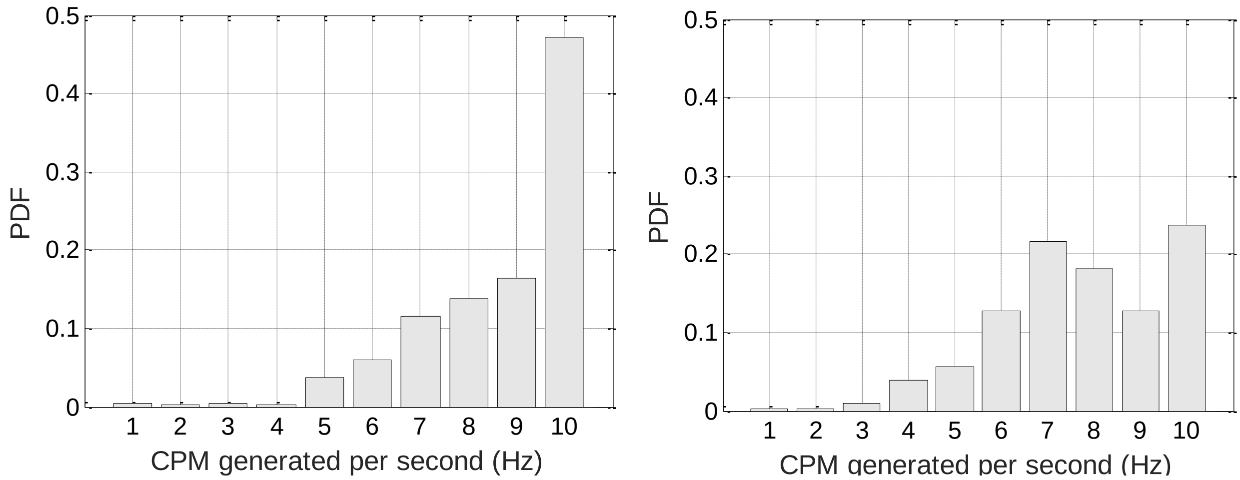
All vehicles are assumed to be equipped with an ITS-G5 transceiver (100% penetration) and operate in the same channel. The propagation effects are modelled using the Winner+ B1 propagation model following 3GPP guidelines [47]. The communication parameters are summarized in Table 5.

Table 5. Communication parameters

Parameter	Values
Transmission power	23dBm
Antenna gain (tx and rx)	0dBi
Channel bandwidth/carrier freq.	10MHz / 5.9GHz
Noise figure	9dB
Energy detection threshold	-85dBm
Data rate	6Mbps (QPSK 1⁄2)

2.2.2.1 Operation

Before analysing the performance and efficiency of each CPM generation policy, it is necessary to understand their operation. To this aim, we focus first on the dynamic policy. Figure 20 represents for this policy the Probability Density Function (PDF) of the number of CPMs transmitted per second per vehicle under the two traffic densities. The number of CPMs generated per vehicle depends on the number of detected vehicles (i.e. traffic density) and on their dynamics (e.g. an object is included in a CPM every 4m). The speed of vehicles is higher for low traffic densities than for higher ones. As a result, vehicles satisfy more frequently one of the three conditions specified in Section 2.1.2.1.3 for the dynamic CPM generation rules (i.e., absolute position changes by more than 4m; absolute speed changes by more than 0.5m/s; 1 second since the last CPM transmitted). Hence, vehicles generate more CPMs per second at low densities (Figure 20.a) than at high densities (Figure 20.b). However, not all vehicles generate CPMs at the same rate in a given traffic density scenario since the speed limit varies per lane (Table 4). It is interesting to analyse with more detail the high traffic density scenario (Figure 20.b). As previously mentioned, the higher the density the less CPMs are in general generated per vehicle since they travel at lower speeds. The vehicles that travel in the higher speed lane move at 70km/h or 19.4m/s. They will then change their absolute position by more than 4m every 0.21 seconds. Vehicles that detect this change then generate a CPM at 4.8Hz on average. However, Figure 20.b shows that there are vehicles that transmit 6-10 CPMs per second. This is because a vehicle generates a CPM as soon as one of the vehicles it detects changes its absolute position by more than 4m. If the detected vehicles change their absolute position by more than 4m at different times, the originator vehicle will need to generate different CPM messages. This explains why CPM frequency rates as high as 10Hz are observed in the highest traffic density scenario (Figure 20.b). It is also important to emphasize that the frequent transmission of CPMs reporting information about a small number of detected vehicles can result in a loss of efficiency due to a higher number of channel access attempts and redundant headers. Such efficiency might be improved by grouping in a single CPM the information of several detected vehicles in a short period.



(a) Low traffic density (b) High traffic density

Figure 20. PDF (Probability Density Function) of the number of CPMs generated per second and per vehicle with the dynamic policy.

Figure 21 represents the PDF of the number of objects included in each CPM for the periodic and dynamic CPM generation policies under the two traffic densities. The figure shows that the periodic CPM generation policies augment the size of CPMs since they include a higher number of detected objects per CPM. This is the case because the periodic policies always include in the CPM all the detected objects, while the dynamic policy selects the detected objects to be included in a CPM based on their dynamics. As the traffic density increases, the number of objects included in each CPM increases with the periodic policies because more objects (i.e. vehicles in our study) are detected. However, Figure 21 shows that the traffic density does not significantly affect the number of objects included in each CPM with the dynamic policy. This is because the speed of vehicles decreases with the traffic density. As a result, vehicles change their absolute position by more than 4m less frequently. Therefore, even if we detect more vehicles due to the higher traffic density, the status of a detected vehicle needs to be reported in a CPM less frequently. The obtained results clearly show the benefits of the dynamic policy since it can adapt the number of objects included in each CPM to the traffic density and speed.

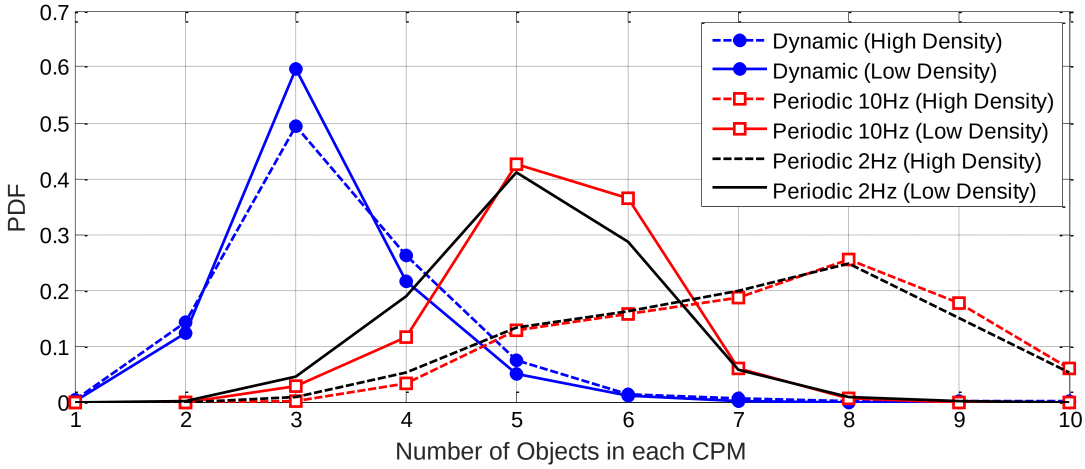


Figure 21. PDF (Probability Density Function) of the number of objects included in each CPM with the dynamic and periodic policies.

2.2.2.2 Communications performance

This section evaluates the impact of the CPM generation policies on the communications performance. To this aim, Table 6 shows the average channel busy ratio experienced when implementing each CPM generation policy under the two traffic densities. The CBR is measured by each vehicle every second. The CBR is a measure of the channel load, and it is defined as the percentage of time that the channel is sensed as busy. A high CBR value indicates that the channel is very loaded and hence risks saturating. If this happens, the communications performance degrades and the packet delivery ratio decreases [49]. On the one hand, Table 6 shows that the periodic policy operating at 2Hz is the one generating the lowest channel load. On the other hand, the periodic policy at 10Hz generates the highest channel load. The dynamic policy generates intermediate channel load levels (Table 6) in line with the results depicted in Figure 20 and Figure 21. These results showed that the dynamic policy generates between 4 and 10 CPMs per second, approximately, and reduces the number of objects per CPM compared to the periodic policies. Consequently, the dynamic policy increases the channel load compared to a periodic policy at 2Hz, but decreases it compared to the periodic policy at 10Hz. Table 6 also shows that the channel load and CBR increase with the traffic density. However, lower increases are observed with the dynamic policy than with the periodic ones. In particular, an increase in the traffic density augments the CBR experienced by the dynamic policy by a factor of 1.6, whereas it increases by factors of 2.2 (2Hz) and 1.9 (10Hz) for the periodic policies. This is again due to the same trend observed in Figure 21. When the traffic density increases, the speed of vehicles decreases and vehicles change their absolute position by more than 4m less frequently. As a result, vehicles generate less CPM messages. Therefore, the impact on the CBR with the traffic density is lower for the dynamic policy than the periodic ones.

Table 6. Average CBR (Channel Busy Ratio)

Policy	Traffic density	CBR
Periodic at 2Hz	Low	7.4 %
	High	16.5 %
Periodic at 10Hz	Low	33.4 %
	High	63.6 %
Dynamic	Low	25.4 %
	High	41.0 %

The channel load or CBR has an impact on the PDR (Packet Delivery Ratio). The PDR is defined as the probability of successfully receiving CPM as a function of the distance between the originating and receiving vehicles. Figure 22 plots the PDR of the periodic and dynamic CPM generation policies under the two traffic densities. The degradation of the PDR with the distance is due to the radio propagation effects. The PDR can also be degraded due to packet collisions or interference when the channel load is high. This effect is highlighted in Figure 22 where the arrows indicate the degradation of the PDR as a result of an increase of channel load and packet collisions when the traffic density increases. Table 6 already showed how the channel load increases with the traffic density. The resulting PDR degradation observed in Figure 22 is hence a consequence of the trends observed in Table 6. Following these trends, Figure 22 shows that the periodic policy operating at 2Hz achieves the highest PDR and the policy at 10Hz the lowest one. Figure 22 also highlights that the dynamic policy achieves a balance between the two periodic policies. However, it is yet to be seen whether the dynamic policy could improve the network performance and increase the PDR by avoiding the transmission of certain CPM messages without degrading the perception capabilities of vehicles.

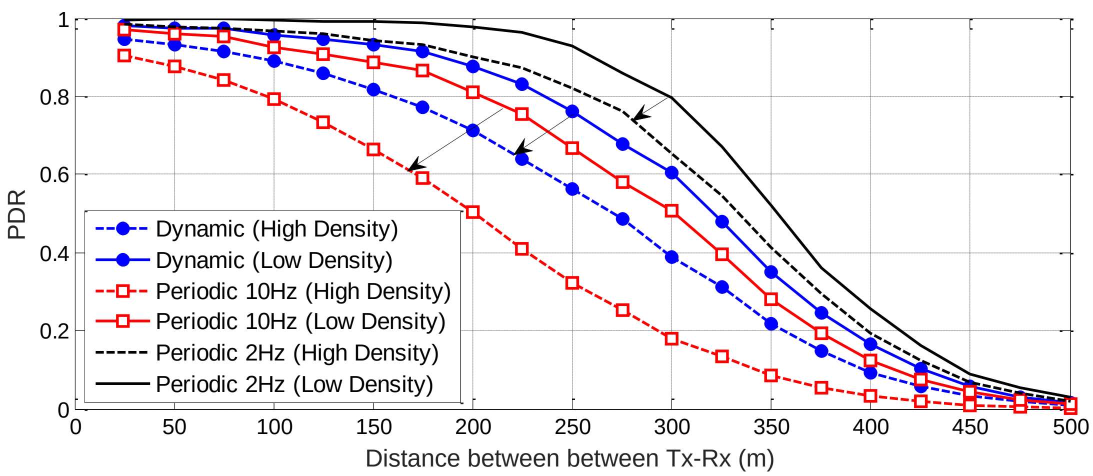
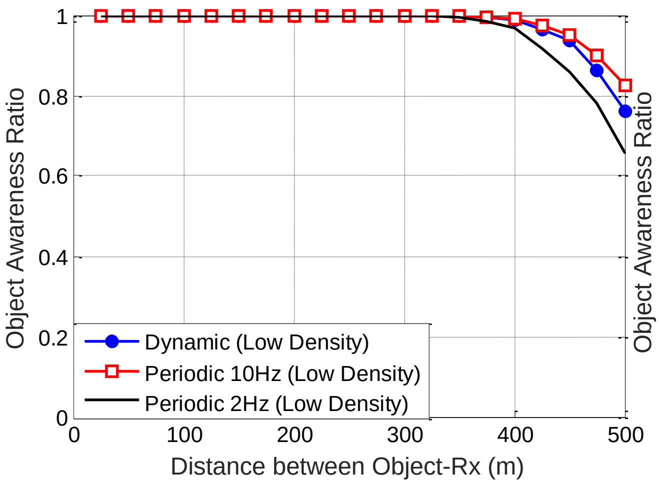


Figure 22. Packet Delivery Ratio as a function of the distance between transmitter and receiver.

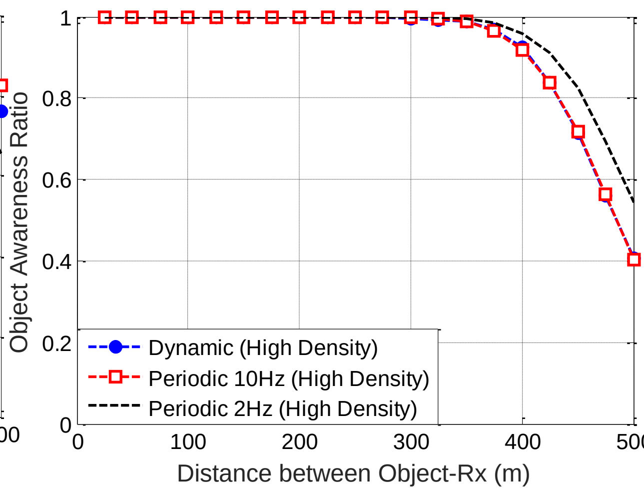
2.2.2.3 Perception capabilities

This section analyses the perception capabilities of vehicles under different CPM generation policies. First, we define the Object Awareness Ratio as the probability to detect an object (vehicle in this study) through the reception of a CPM with its information in a given time window. We consider that an object is successfully detected by a vehicle if it receives at least one CPM with information about that object within a given time window. Then, we compute the Object Awareness Ratio for three different time windows (i.e. 1s, 0.5s and 0.1s). Figure 23 depicts the average Object Awareness Ratio as a function of the distance between the detected object and the vehicle receiving the CPM. The results are shown for the periodic and dynamic policies and the two traffic densities.

The results obtained in Figure 23 show that when the time window is equal or higher than 0.5s, all policies achieve a high object awareness ratio (higher than 0.987) up to 300m (see Figure 23 from a to d) independently of the traffic density. As shown in Figure 23.b and Figure 23.d, beyond 350m, the awareness ratio degrades under higher densities for the dynamic policy and the periodic policy at 10Hz. This is the case because of the higher CBR (Table 6) and lower PDR levels (Figure 22)[1]. On the other hand, Figure 23.a and Figure 23.c show that from 350m a higher degradation of the awareness ratio is observed for the periodic policy at 2Hz under low traffic densities. This is because at such distances the propagation effect becomes dominant when the traffic density is low (there are less packet collisions). All CPM generation policies experience the same degradation due to the propagation since it is not dependent on the channel load. However, propagation losses affect more negatively the Object Awareness Ratio for the periodic policy at 2Hz since this policy transmits less CPMs. To further study these effects, Figure 23.e and Figure 23.f show the Object Awareness Ratio for all the policies when the Time Window is set to 0.1s. In this case, the periodic policy at 2Hz cannot achieve a high Object Awareness Ratio performance even at short distances due to the low number of CPMs generated per second. The results reported in Figure 23.e and Figure 23.f show that only the periodic policy at 10Hz can achieve an Object Awareness Ratio close to 1 at short distances under this scenario. The dynamic policy, compromises CPM generation rate to reduce the channel load (Table 6) and therefore improves the communications performance (Figure 22). If we compare the dynamic policy with the periodic policy at 10Hz, we observe that it degrades the Object Awareness Ratio but still achieves a performance above 90% and 80% up to 250m and 225m under low and high traffic densities, respectively, for a time window 0.1 seconds.

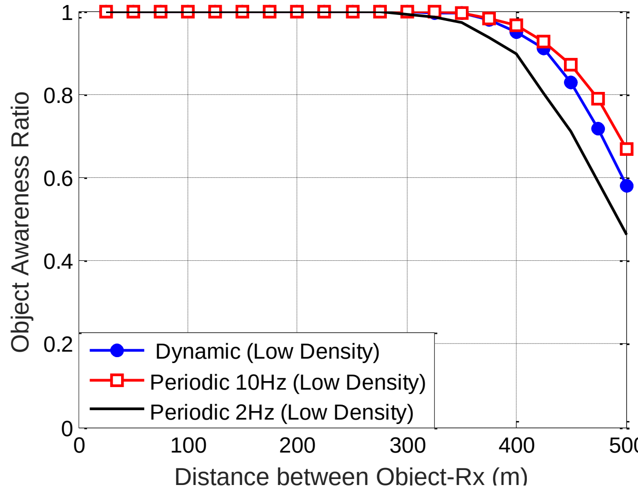


a) Time window 1 second (low density)

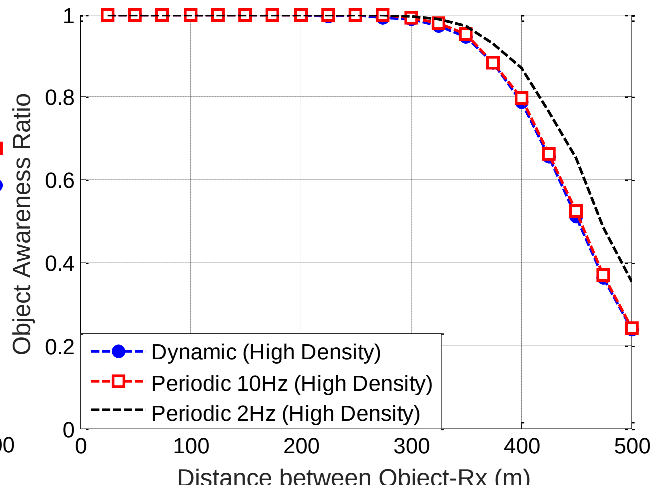


b) Time window 1 second (high density)

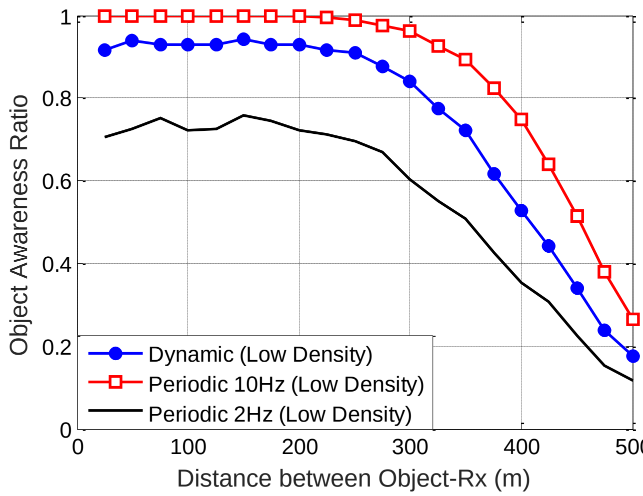
[1] It is important to remember that the PDR is calculated as a function of the distance between two vehicles (originating and receiving vehicles), but the Object Awareness Ratio accounts for objects detected by any vehicle. In this context, the Object Awareness Ratio might refer to an object that is 300m away from the vehicle receiving the CPM, and the vehicle detecting the object and sending the CPM might be at 250m for example.



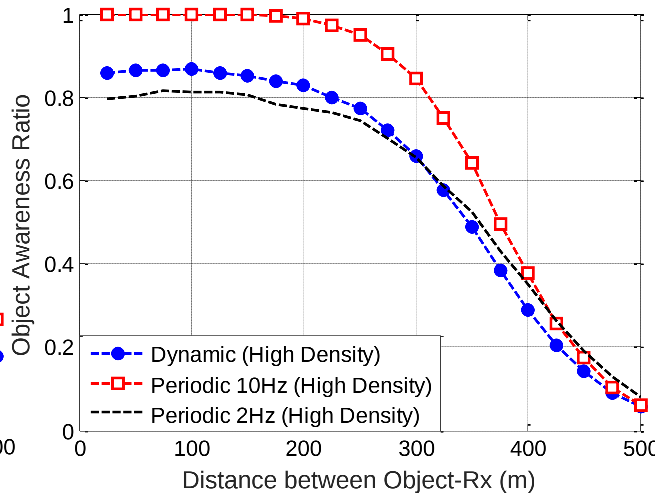
c) Time window 0.5 seconds (low density)



d) Time window 0.5 seconds (high density)



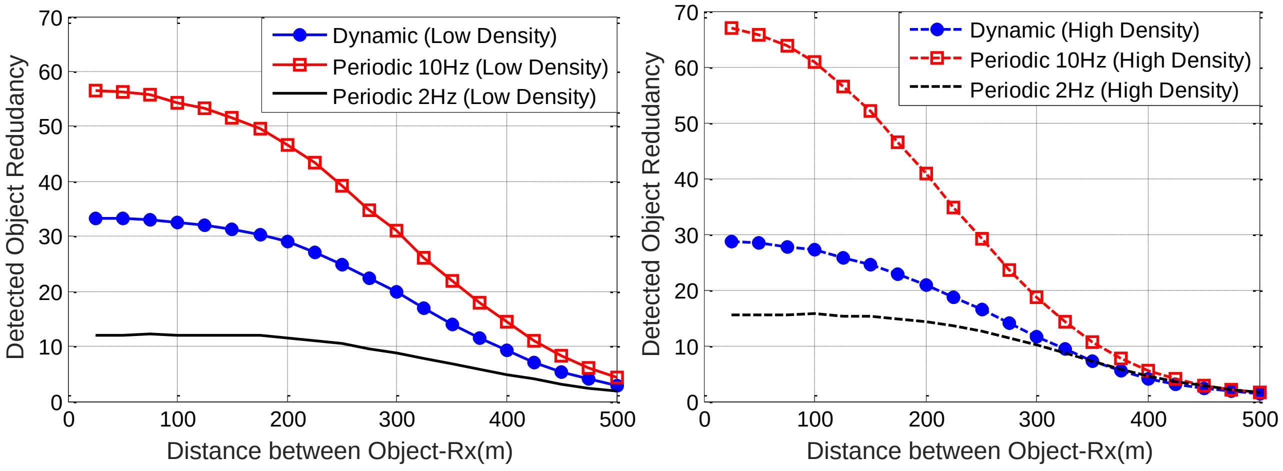
e) Time window 0.1 seconds (low density)



f) Time window 0.1 seconds (high density)

Figure 23. Object Awareness Ratio as a function of the distance between the detected object and the vehicle receiving the CPM.

The obtained results show that all CPM generation rules provide high Object Awareness Ratio performance. However, we have seen in Table 6 and Figure 22 that the CPM generation policies can generate non-negligible channel load levels that can degrade the communications performance and affect the network's scalability. It is hence necessary to evaluate whether the current CPM generation policies generate unnecessary redundancy about the present objects or vehicles in our driving environment. The Object Awareness Ratio is calculated considering all CPM messages received within the time window. Therefore, it is interesting to analyse the CPMs received that contain the same object. Figure 24 illustrates the number of updates received per second about the same object through the reception of CPMs. This metric is referred to as detected object redundancy and is depicted in Figure 24 as a function of the distance between the object and the vehicle receiving the CPM for both low (Figure 24.a) and high (Figure 24.b) traffic densities. The degradation observed in Figure 24 with the distance is a direct consequence of the PDR degradation reported in Figure 22. Figure 24.a and Figure 24.b show that the periodic policy at 10Hz provides around 55 updates (low density, Figure 24.a) and 63 updates (high density, Figure 24.b) per second of the same object at short distances (roughly, for short distances, i.e. PDR close to 1, this would mean that ~5 or ~6 vehicles are detecting the same object under low and high traffic densities, respectively). The dynamic policy can reduce this value to 33 updates (low density, Figure 24.a) and 28 updates (high density, Figure 24.b) per second and object without degrading the Object Awareness Ratio (Figure 23).

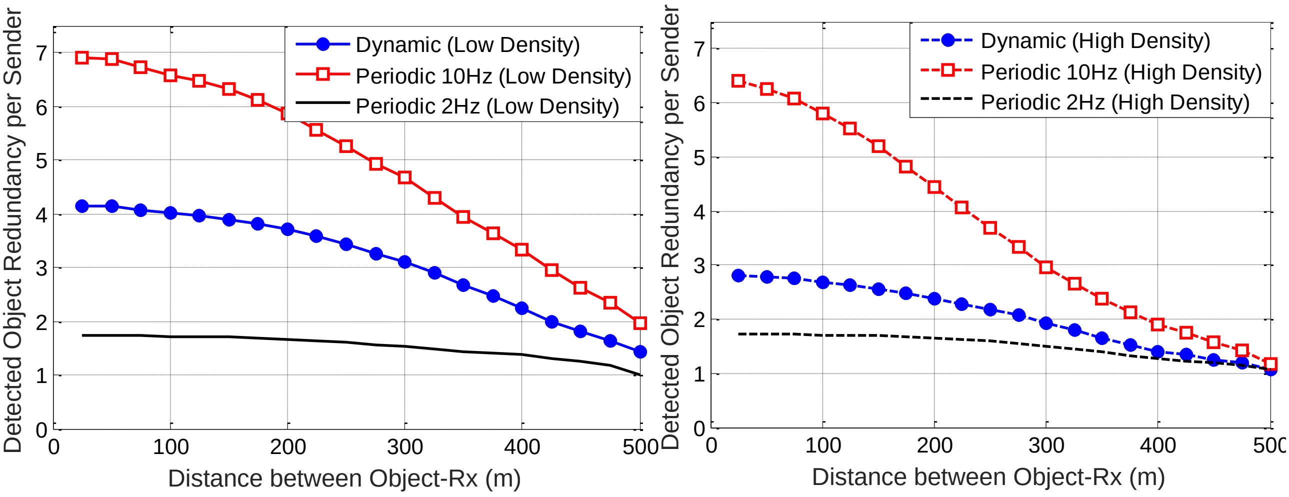


a) Low Density b) High Density

Figure 24. Detected object redundancy as a function of the distance between the detected object and the vehicle receiving the CPM.

Figure 24 showed the redundancy generated by the current CPM generation policies from the point of view of the vehicles receiving the CPMs. To further investigate the redundancy of CPM generation policies, Figure 25 analyses it from the point of view of the vehicle that sends the CPM messages. In particular, Figure 25 illustrates the number of updates per second a vehicle receives about the same object and that have been transmitted by the same sender. This metric is referred to as detected object redundancy per sender and is depicted in Figure 25 as a function of the distance between the object and the vehicle receiving the CPM for both low (Figure 25.a) and high (Figure 25.b) traffic densities. Similar to Figure 24, Figure 25 shows that the periodic policy at 10Hz provides around 6.8 updates (low density, Figure 25.a) and 6.2 updates (high density, Figure 25.b) per second of the same object at short distances from the same sender. The dynamic policy can reduce these values to 4.1 (low density) and 2.8 (high density) updates per second and object without degrading the Object Awareness Ratio (Figure 23).

The results reported in Figure 24 and Figure 25 show that the redundancy in the periodic policies at 10Hz and 2Hz increases with traffic density. On the contrary, the dynamic policy actually reduces the redundancy with the density. This is because as the traffic density increases, the vehicles' speed reduces, which reduces the CPM generation rate as defined in the generation rules for the dynamic policy (see Section 2.1.2.1.3). Due to this fact, the dynamic policy can reduce the channel load (Table 6) and improve the communications performance (Figure 22). Despite the gains observed with the dynamic policy, it is yet an open issue whether the still high redundancy levels observed in Figure 24 and Figure 25 are necessary for a safe cooperative and automated driving or not. The dynamic policy could be modified to further decrease the redundancy and increase the robustness and scalability of the vehicular network as it is a key component to achieve the expected benefits of cooperative and automated driving.

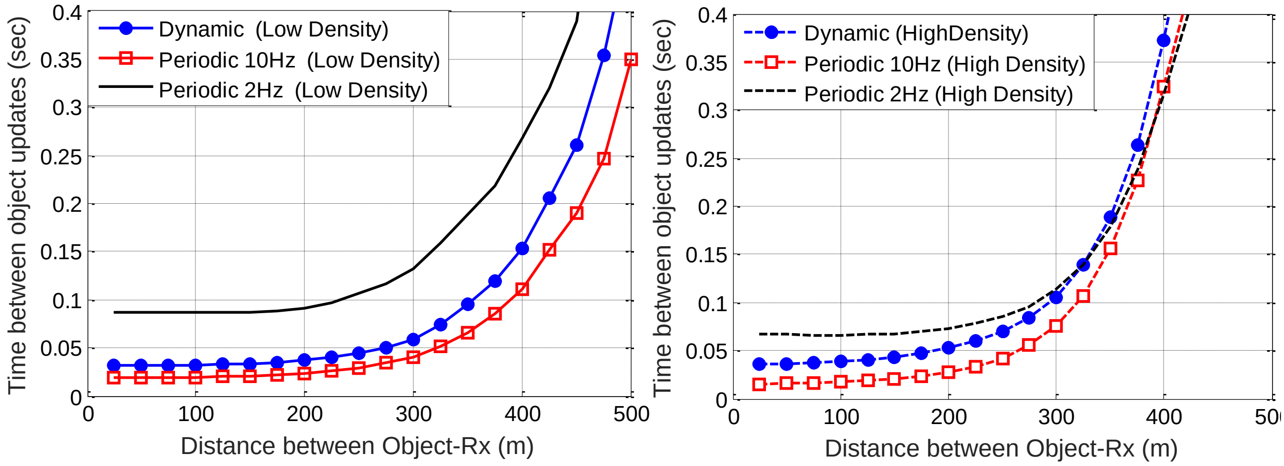


a) Low density b) High density

Figure 25. Detected object redundancy per sender as a function of the distance between the detected object and the vehicle receiving the CPM.

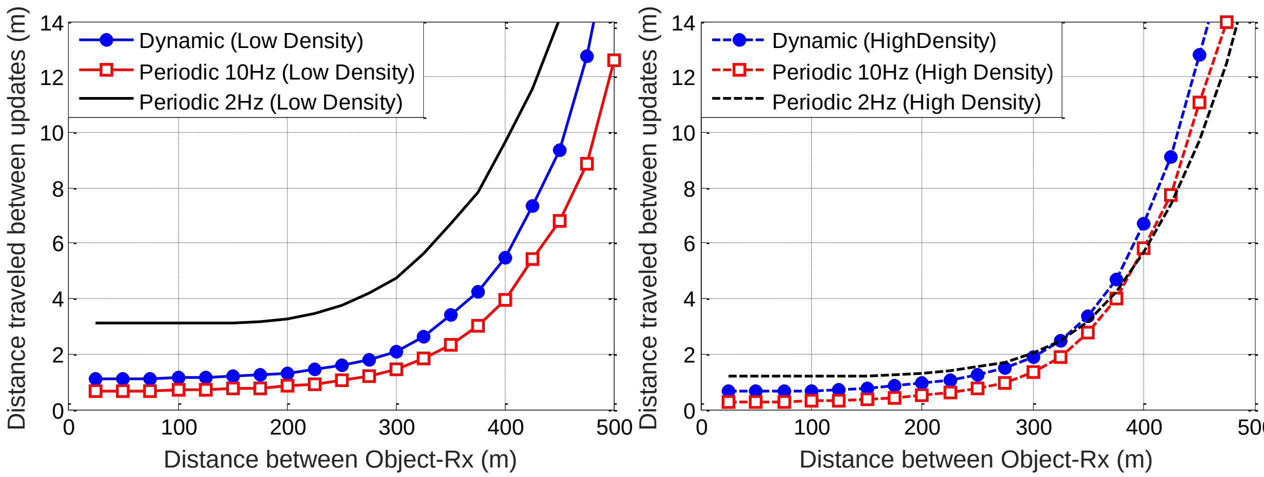
The value of collective perception or cooperative sensing depends on how timely or fresh is the information received about the detected objects. A vehicle cannot base its driving decision on outdated information. Figure 26 plots the time between two successive received CPMs with information about the same object or vehicle. The metric, referred to as the time between object updates, is represented as a function of the distance between the object and the vehicle receiving the CPMs for both low (Figure 26.a) and high (Figure 26.b) traffic density scenario. To further investigate the timeliness of the received information, Figure 27 plots the distance travelled by objects between two successive received CPMs with information about the same object or vehicle. In this case, the metric is named distance travelled between updates and is represented as a function of the distance between the object and the vehicle receiving the CPMs for both low (Figure 27.a) and high (Figure 27.b) traffic density scenario. It is important to emphasize that the CPMs including information about the same object or vehicle might be transmitted by different (multiple) vehicles.

Figure 26 shows that all CPM generation policies provide object updates below 0.1s for low density (Figure 26.a) and 0.08s for high density (Figure 26.b) up to 200m approximately. These time values are reduced to less than 0.04s (Figure 26.a) and 0.06s (Figure 26.b) with the dynamic policy. Alternatively, Figure 27 shows that all CPM generation policies approximately provide updates of objects that have travelled less than 4 meters (low density, Figure 27.a) and 2 meters (high density, Figure 27.b) up to 250 meters. These values reduce to 1.6 meters (low density, Figure 27.a) and 1.25 meters (high density, Figure 27.b) with the dynamic policy. It is important to note that for the two metrics (Figure 26 and Figure 27) the objects updates are fresher under high traffic density for the periodic policies. This is because the number of vehicles reporting about the same object increases with the traffic density. However, with the dynamic policy the time between object updates and the distance travelled between updates are increased when the traffic density increases, because vehicles reduce their speed and CPMs are generated less frequently.



a) Low density b) High density

Figure 26. Average time between object updates as a function of the distance between the detected object and the vehicle receiving the CPM.



a) Low density b) High density

Figure 27. Average distance travel of an object between updates as a function of the distance between the detected object and the vehicle receiving the CPM.

2.3 Second iteration

2.3.1 TransAID Sensor Fusion

This section discusses the approach chosen in TransAID for the sensor fusion. Separate subsections discuss the road infrastructure at motorways with C-ITS data, camera sensor fusion and vehicle sensor fusion.

2.3.1.1 Infrastructure

In this document, Section 2.2.1.1 discussed the research work of sensor fusion approach in Service 2 for the first iteration, where the road infrastructure at motorways with C-ITS data, camera sensor fusion and vehicle sensor fusion are discussed in subsections. In this section, the same approach of sensor fusion in Service 2 for the second iteration is followed, where an additional traffic management component, the ramp metering at the on-ramp infrastructure side, is added to the sensor fusion.

Sensor technology is a vital component used for data collection for V2X based communications, such as Vehicle-to-Vehicle (V2V) and Vehicle to Infrastructure (V2I). Mixed traffic with variating shares and novel characters of autonomous or self-driving vehicles brings unpredictability to motorway merging that is closely related to cooperative sensing in ITS. Traditional models for post-processing traffic data provide the base model for different merging algorithms. However, more importantly, enhancements are in need to utilize emerging sensor technology to achieve sensor fusion that shows augmented performance, as shown in Figure 10.

Modern vehicles with different autonomous level are equipped with multiple sensors to measure their operation condition as well as its surroundings, such as the road condition. Sensor fusion on the vehicle side will be discussed in Section 2.3.1.2. On the infrastructure side, two categories of sensors can be classified based on their locations: intrusive and non-intrusive sensors. Most intrusive sensors are wired/wireless and they are installed on pavement surfaces, among which, the inductive loop detectors are the most commonly applied ones on the road.

Figure 28 shows examples of inductive loop detectors on the urban road (left picture) and highway (right picture). In general, inductive loops are wire coils buried into roads and send data to processing units. Because of the simplicity of design principle, high accuracy and long life cycle against extreme weather, this group of sensors is of wide usage on current road network. It is used for detection of vehicle's movement, presence, count, occupancy and average speed, depending on whether it is traditional loop detector or double loop detector (see Section 2.2.1.1.1). The generated signals are recorded in a detector station at the roadside, and the data are further sent to roadside stations and other more centralized systems.

Like nerve endings, inductive loop detectors are the basic elements to measure and collect traffic data. The density of inductive loop detectors varies from every 100-150 meters (urban road) to 300-500 meters (on the highway), or even more diluted in some area. On the roadside, existing detector stations provide the source of power and a cabinet to house data collection equipment. These data are then sent to roadside stations, and then to centralized traffic systems.

Figure 28 Inductive loop detectors on the urban road (left) and motorway (right). (Source: Henk Taale, ITSEDULAB)

In the Netherlands, the major road network is covered with loop detectors, detector stations, local stations, regional and national traffic systems. To maintain network wide traffic management, Rijkswaterstaat has developed MoniCa (MONItoring CAscade), a system that centralizes detection data from these loop detectors [69]. Detected data types are traffic compositions, traffic congestions (peak hour congestions and shockwave congestions), average speed and intensity with an update frequency of every minute. After collecting these data, MoniCa process them in order to be used by ITS system. There are in total seven MoniCa sub-systems throughout the country where real-time traffic data can be shared. In addition, detected data from loop detectors are also sent to (or via MoniCa) MTM (Motorway Traffic Management), a fully automatic motorway management system, which is developed to monitor the traffic flow on main highway [68]. Unlike MoniCa, which provides wide range data of the network, MTM is used for detection of vehicle speed and traffic intensity in order to enable AID system (Automatic Incident Detection), traffic lights and DRIP (Dynamic Route Information Panel) on the motorway. For the latter two (traffic lights and DRIP), MTM needs facilitation from MoniCa. On the motorway, MTM consists of inductive loop detectors every 300-500 meters. For road segments that has no MTM coverage, MoniCa is the main system and the installation density of loop detectors can be less.

The inductive loop detector system is a relatively accurate system to measure vehicle speed and traffic intensity. Regarding measurement of vehicle length, the built-in detectors algorithm affects its accuracy, since it calculates with the magnetic profile of the vehicle signature when it passes through (see Section 2.2.1.2). Considering special vehicle categories such as motorcycles and cyclists, on the one hand, although most inductive loop detectors have no problem detecting a motorcycle, they can still miscount motorcycles due to the fact that the loop is smaller than a lane and miscount can happen when a motorcycle goes through between lanes with no loop coverage. On the other hand, the inductive loop detector can miss cyclists and motorcycles due to the low metal content, especially equipped with upcoming carbon technologies. The following advantages and disadvantages of inductive loop detectors has been identified, according to [68]:

-*Advantages:*

1. In principle, loop detectors are the most trust-worthy and accurate detection system. It is a mature technology with wide applications.
2. Loop detectors have a long life cycle, 20 to 30 years depending on the situation
3. They have low disruption and breakdowns due to its stable character of hardly wear and tear.
4. Loop detectors are not sensitive to extreme weather conditions, although it might be susceptive to heavy frost.

-*Disadvantages:*

1. The installation of loop detectors needs to close down certain road segments, therefore the installation and maintenance is expensive.
2. The extra layer of asphalt can reduce the sensitivity of detection.
3. With low speed (<20km/hr), the accuracy deteriorates.
4. The locations of these detectors are fixed while the infrastructure planning are more and more dynamic in reality.

Table 7 Accuracy overview of typical inductive loop detectors in the Netherlands

Features	Accuracy (in percentage)
Traffic count	95-99
Average travel speed	96
Vehicle length	95
Vehicle classification	95
Detectable speed range	0~400 km/hr
Detection availability	97~100
Robustness	Affect by extreme weather circumstances (e.g. heavy frost) and road maintenance
Installation	Closed down on lanes/road sections

The accuracy of traffic management systems with inductive loop detectors as data source reduces according to literature. In the report of Van Lint et al. [69], it was indicated that 12% of all raw detection data (time average speed and intensity) from MoniCa system are either unreliable or completely missing. In addition, van Lint indicates that there are outliers of 25% or more, these outliers are often caused by overdue maintenance work.

When mixed traffic of LV, CV and C(A)V with diverse driving behaviours are involved, traditional loop detection is still the main source of detection input data but its discontinuous data with low granularity on road segment is not sufficient anymore, e.g. for TransAID's Service 2 highway merging scenario. Therefore, a non-intrusive detector: a *TrafiRadar* is implemented on a viaduct above the highway merging area to overlook the on-ramp and mainline highway below, where they merge and number of lanes reduces from 3-lane to 2-lane.

A camera provides many of the functions that an inductive loop detector provides with fewer difficulties. As a sensor, cameras are less widespread than inductive loop detectors. This is because they are expensive and may be affected by environmental conditions, such as: snow, rain, and fog, among others. Normally, cameras are used to develop applications that provide information on a selected location, such as queue detection at a traffic light, traffic conditions, and traffic rule violation. The location of these camera sensors are usually above ground level, mounted on a mast, a gantry or a bridge, which lead to the challenge of installation.

For TransAID Service 2, the position of the camera is chosen to be on the side of the viaduct above the highway, in order to have a sufficient view range of the merging area. Accurate traffic data via this detector is of utmost importance before fusing with another data source under the sensor fusion algorithm. As known, cameras are subject to being spotted by drivers, resulting in different and faster reactions such as: slowing down, using the correct drive lane, and being more cautious after detecting those devices. In this case, the camera is installed on a viaduct right upstream to the merging area below, to monitor from a behind perspective instead of frontal perspective, so that merging behaviours do not deviate due to distraction from spotting the camera. The working mechanism of the *TrafiRadar* in this use case is explained in Section 2.1.1.2.2.

Other proliferation of alternative data and information sources provide data that compliment traditional sensor measurements. Floating car data is one of these sources. The time-stamped locations and speeds come directly from the moving vehicles, utilizing GPS, emerging connected (and automated) vehicles technology and collective perception concept at infrastructure nodes. Hence, at the infrastructure nodes, intelligent sensors within the physical infrastructure are constantly being deployed and maintained. The success of sensor fusion on the infrastructure side largely depends on the platform used to access, collect, and process accurate data from the environment. At the current stage, Service 2 only includes LVs and CVs (non-automated vehicles where in-vehicle sensors are not equipped). The road infrastructure equipment at motorways with C-ITS data, camera sensor fusion are even more important. At later stages, when autonomous vehicles are allowed in high speed merging situation, the components of an automated vehicle can fail, so redundancy must be built into the vehicle. Infrastructure side collective sensing and data fusion present such an opportunity to these automated vehicles.

To sum up, collective perception of Service 2 enables the exchange of sensor information: inductive loop detector data, camera data and cooperative sensing data from connected vehicles. Sensor fusion utilize different types of traffic flow sensors installed along the roadway and the data fusion strategies that augmented the performance of these data. This is to improve traffic safety in merging area with mixed traffic and the traffic efficiency of onramp to mainline highway merging.

Comparing to the first iteration where the data model groundwork (such as traffic model for merging assistant in Figure 10) has been performed, sensor fusion in the second iteration adds a new element: the implementation of a ramp metering and entry loop detector on the onramp see Figure 29.

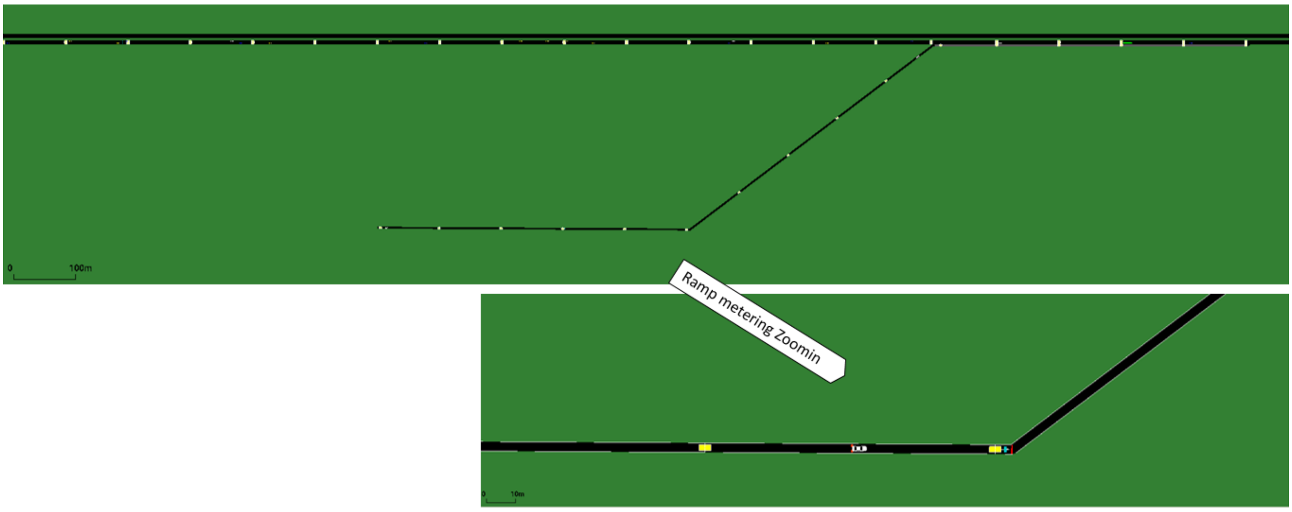


Figure 29 Ramp metering (snapshot below showing red) and entry loop detector on the onramp of Service 2

Despite specific variation from region to region, Ramp Metering (RM) has been a mature and common deployment on the on-ramps. The objective of the ramp metering is maximum utilization of the onramp to maintain free flow condition on the mainline of the motorway. Although the compliance rate of individual vehicle following a ramp metering instruction is high, the effect of each metering is quite different due to disturbances during merging maneuverer. When it comes to mixed traffic, the effect will become more uncertain since the automated vehicles with various SAE level follow different car following and merging algorithms.

To increase the unification of car following and merging behaviours, the implemented ramp metering in Service 2 in the 2nd iteration of TransAID is supported by the merging assistant algorithm. This new element takes into account the future merging behaviours, directly integrated into the logic of when to turn the ramp metering green.

The current design of the ramp metering in the simulation environment SUMO has the following specifications: minRed = 1second, green = 1second. The principle is to continuously search for possible merging gaps every time step (0.1 second), based on the entry loop detector data on the mainline highway upstream (rightmost lane) and the entry loop detector data on the on-ramp. Unless there is a possible gap in the future, the ramp metering will keep at the stage of red for at least 1 second. Effectively, the base model in Figure 10 is supported with more predictable vehicle speed (0 km/hr or current speed retrieved from entry loop detector right in front of the RM), regardless of vehicle types and car following behaviours.

To calculate future gaps, the RM applies the merging assistant algorithm, which embody the sensor fusion model in the previous time step. The enriched and complete sensor fusion model in Figure 10 are iteratively applied to the intelligent RM. The aforementioned extended sensor fusion model is first implemented in simulation environment SUMO in D4.2 [5]. Although still considered as low-level fusion, the simulation has proven that sensor fusion can handle vehicles which are expected to accelerate following a predictable pattern.

In the 2nd iteration of infrastructure sensor fusion, more preparations are made for field deployment. Therefore, we use configuration file from real world RSUs. It is first tested in the simulation environment, where the RSU.java can load JSON topologies with Lat-Long ITF file/x-y coordinates from SUMO. Moreover, speed advice for CVs on the mainline highway (rightmost lane) is also supported with CACC functionality. If speed advice for CVs on the mainline highway are given, they follow the given advised speed and updates of current speed are fed to extended sensor fusion model, similarly to the speed advice for on-ramp CV in the 1st iteration. This facilitate the update of gap searching the creation more effectively.

The following two figures are described in D5.4 Signalling for informing conventional vehicles. These two figures give visual representation of the merging assistant algorithm based, in vehicle and roadside applications that are fundamentally based on extended sensor fusion on the infrastructure side and V2X-based cooperative sensing.

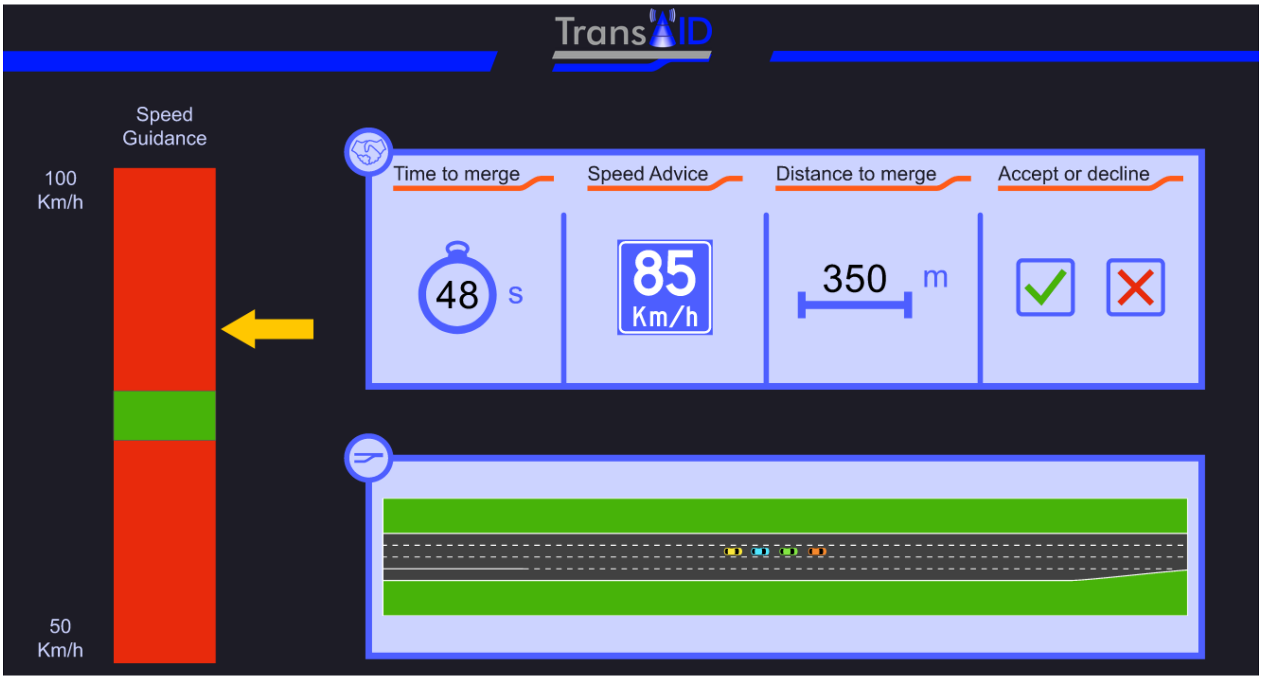


Figure 30 In-vehicle application based on extended sensor fusion model of Service 2

Figure 31 Roadside application based on extended sensor fusion model of Service 2

2.3.1.2 Vehicle

As described in section 2.2.1.2 the sensor fusion strategy is composed of a low-level LIDAR fusion module and an object-level fusion module. The object-level fusion module associates and fuses the vehicle sensor data with the data received via the V2X messages. V2X data fusion comprises the merging of measurement data of an ego vehicle with the measurement results of other sensors, e.g. infrastructure-based sensors or sensors of neighbor vehicles. Given the measurements of different sensors, the accuracy of state estimation of a road vehicle can be improved.

A detailed model of the implemented object-level fusion is shown in Figure 32. A first step is to filter out clutter objects from the vehicle sensor data to avoid unnecessary computations and reduce computation time. Another important step in the fusion pipeline is the velocity model. This module is necessary as it compensates for the time having passed between the object being recorded by the infrastructure camera and receiving the CPM message in the vehicle. When using a state of the art surveillance camera, image compression, image transport over Ethernet and image evaluation need time. Therefore, object states arrive to the vehicle within some delay. Typical delays are 200ms ~ 400ms. A vehicle moving at a speed of 50 km/h travels around 2,8m and 5,5m within this delay.

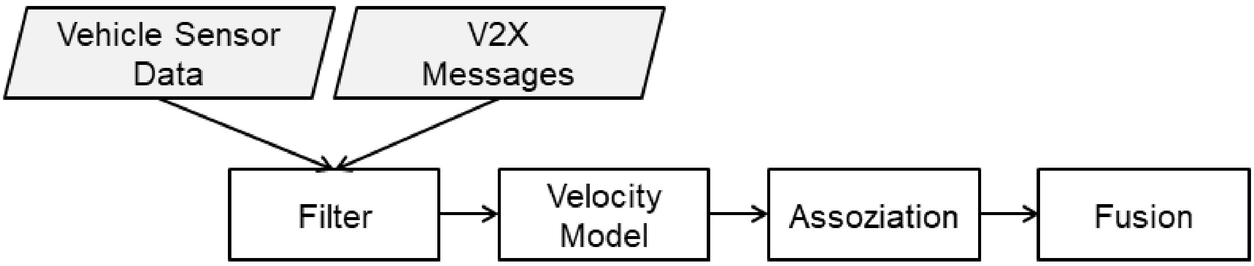


Figure 32: Overview of the software components for the object-level fusion.

Another important aspect about the velocity model is concerning the time synchronization between the road site unit and the vehicle. If the time is not synchronized with high precision on both ends, this leads to significant deviations, when predicting the current position of the objects transmitted via V2X. If possible, the GPS time of the transmitting and the receiving unit offer a good solution of synchronized time.

Since it is critical to keep the delay between recording the objects and receiving them in the vehicle as minimal as possible, the tracking step on the RSU is changed to an adapted version of the SORT approach presented in [71]. This tracking approach is based on a Kalman filter that performs the prediction step based on a constant velocity model. From the predicted tracks and the new detection, a cost matrix is composed of their inverse intersection over union (IoU). Based on the cost matrix, the predicted tracks are matched to the new detections with linear assignment. During the assignment, confirmed tracks of objects that have already been tracked over multiple time steps are associated first. Furthermore, consistently tracked objects are processed prior to tracks with gaps in their tracking history. Associated tracks and detections are subsequently used to update the Kalman filter. Unmatched detections on the other hand, generate new track candidates. This outlines the process that is used in the second iteration to track the detected objects over time in order to determine object velocities, reduce uncertainties and also provide object histories.

While this new tracking approach works in real time, it does not achieve the same accuracy as the approach comprised of the optical flow described in 2.2.1.1.2.2 together with the tracking modeled as an optimization problem as described in 2.2.1.1.2.3. In order to still achieve better results, it is therefore vital to improve the detection of the objects by retraining the detection CNN. Since labelling of new training data is a very time consuming process, this is done in a semi-supervised way, with the aid of the offline tracking approach described for the first iteration. The result of the offline tracking on an image from a RSU is shown in Figure 33.

Figure 33: Result of the offline tracking approach on a RSU image

For the process of generating more training data, first a Faster R-CNN model pre-trained on the COCO dataset [74] is fine-tuned on a manually labelled dataset. The detection produced by this network can be seen in the upper image of Figure 34. Since the offline tracker is able to provide a much better result compared to this detection, the result from the tracker shown in Figure 33 is used as new training input for further fine-tuning the Faster R-CNN network. In this way, the detection is iteratively improved with more accurate training data being available each time. The lower image in Figure 34 shows the detections from the newly trained network with the additionally provided training data. Comparing both images, the number of false detections is visibly reduced with the retuned network, yielding a more accurate perception.

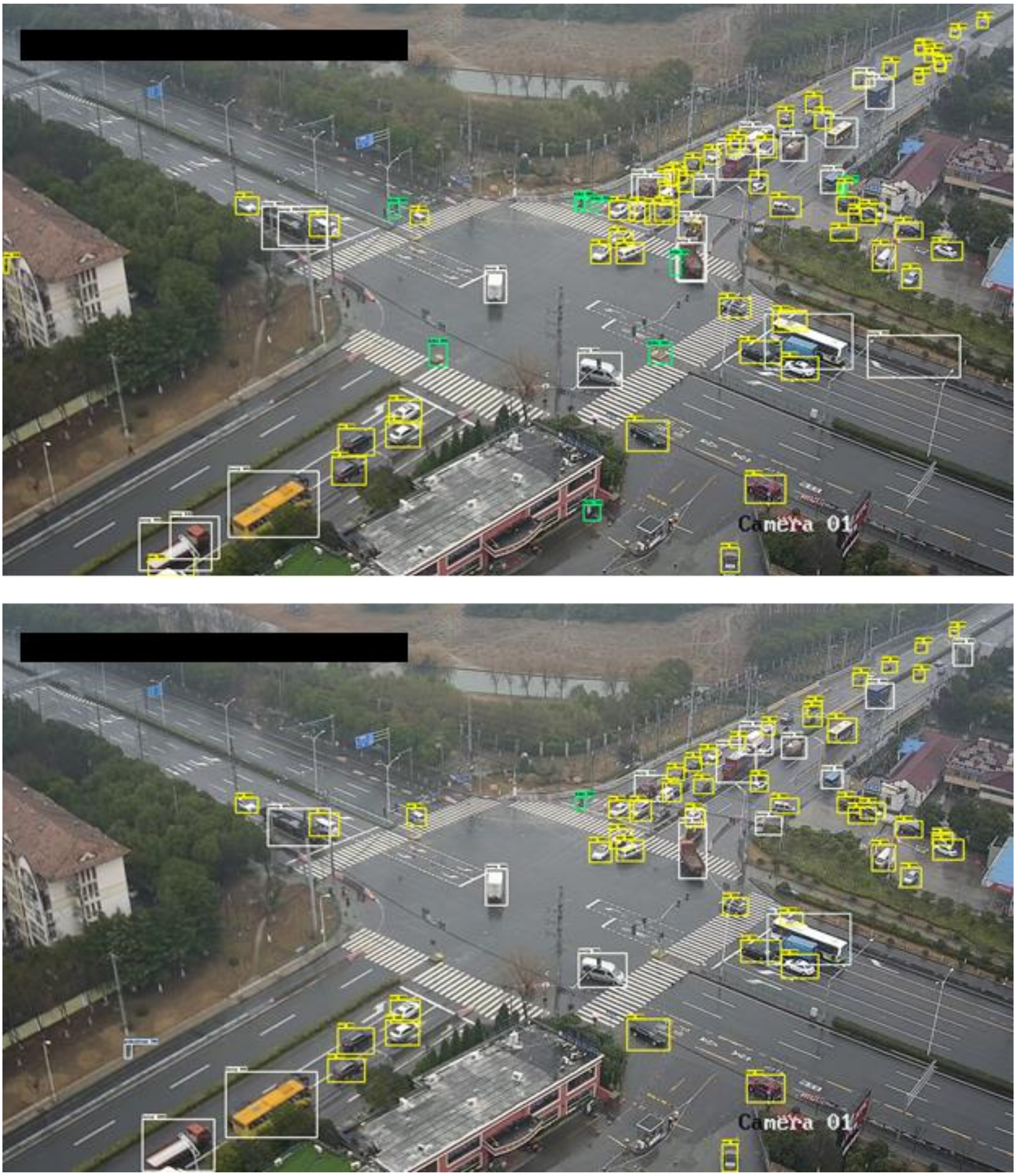


Figure 34: Result of the detection with a Faster R-CNN before (upper image) and after (lower image) the fine-tuning on the additionally labeled dataset

This observation of improved accuracy in the detections can also be made for new unseen data examples as shown in Figure 35. Here new data from a different day was evaluated with the network trained on just the manually labeled data. This can be seen in the upper image, while the lower image shows the results of the network fine-tuned on the additionally labeled data.

Figure 35: Result of the detection on unseen data with a Faster R-CNN before (upper image) and after (lower image) the fine-tuning on the additionally labeled dataset

In all cases, no masking of the images is used and all detections with a confidence above 0.65 are displayed. However, the test sites equipped with an RSU vary, as well as the utilized camera and mounting height. Since this produces images with different perspectives, as seen in Figure 36, fine-tuning the networks to the individual locations seems very relevant. The comparison between the middle and the lowest image in Figure 36 shows the difference in performance, when using a network fine-tuned to the perspective. While the Faster R-CNN network that produced the detections depicted in the middle image was not trained on any data from a similar perspective, the Faster R-CNN network producing the detections in the lowest image was trained on additional training data from another scene recoded by the same RSU. Furthermore, reducing the amount of different labels to more general classes, that are found in all regarded scenes, lead to an overall improvement of the detections. For this reason the ten labels (car, car with trailer, van, bus, lorry, lorry with trailer, articulated lorry, pedestrian, motorbike, bicycle) to be detected in the upper image in Figure 36 were reduced to five labels (car, bus, lorry, pedestrian and bike) in the middle image. A slight improvement is noticeable, even though the upper image network is a Faster R-CNN network with the more complex ResNet-101 backbone compared to the middle and lower image network, which is a Faster R-CNN with the less complex Inception V2 backbone.

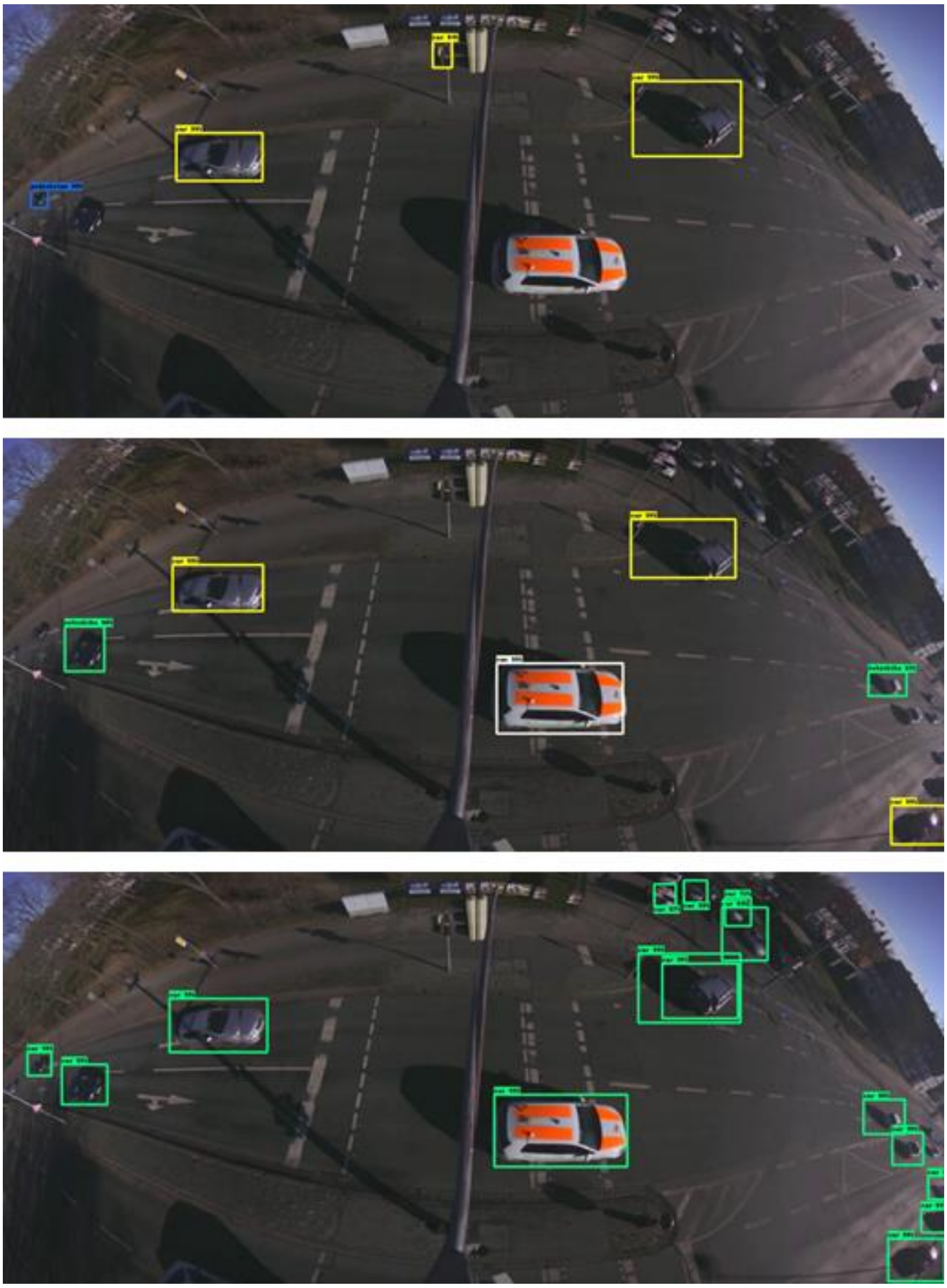


Figure 36: Result of the detection with a Faster R-CNN with ResNet-101 backbone and ten classes (upper image), with Inception V2 backbone and five classes (middle image), with Inception V2 backbone, three classes and additional training data (lower image).

Once the detected and tracked objects from the RSU are received and preprocessed in the vehicle, the association with the in-vehicle data builds the core of the track-level fusion. As described for the first iteration, the implemented solution for the association task in the fusion pipeline is based on [46] and establishes track-to-track correspondences between the tracks contained in the V2X messages and the ones derived from the in-vehicle sensors. The association depends on the correct localization of the ego vehicle itself, and on an accurate projection from image coordinates into the 3D coordinate system of the RSU. The environment model of an automated vehicle comprises state vectors of all vehicles in the vicinity of the ego-vehicle. These vehicle states include position, speed and angle of the driving direction. However, a state of the art CNN based road vehicle detector does not give an object pose estimate. On the other hand, object pose estimates are needed for pose tracking and determining the covariance matrix of the estimation error. The covariance matrix is in turn needed for the covariance intersection algorithm used for the track-level fusion step in the ego-vehicle. One possible countermeasure to circumvent or reduce the problem of the back-projection of 2D bounding boxes in image coordinates into 3D objects in camera relative coordinates and the lack in the covariance matrix, is to perform 3D pose estimation instead of detection only 2D bounding boxes. An example from the KITTI dataset [75] of the desired output from the 3D pose estimation is shown in Figure 37.

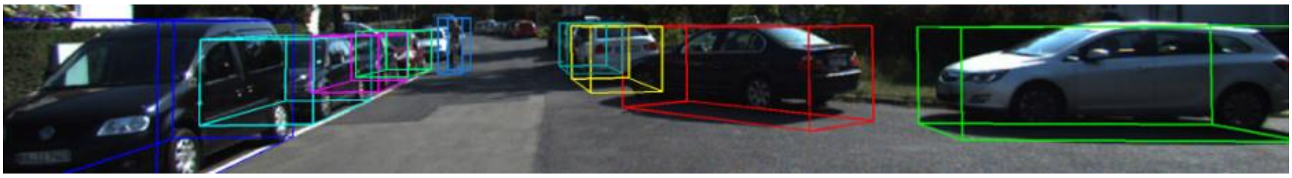


Figure 37: Exemplary output of the 3D pose estimation [75]

One reason for using a hemispheric camera for the roadside surveillance is the cost benefit. The concept of roadside assisted data fusion is not viable as long as the cost for equipment is high. One approach for saving cost is using a hemispheric camera, as it can cover a whole intersection from one mounting point. However, the changes in perspective within the images of a hemispheric camera are more severe compared to traditional cameras. Therefore, the need for pose estimation is higher and pose estimation itself is more challenging with a hemispheric camera. Therefore, also a dedicated concept for tracking is needed. The concept needs to account for the large changes in perspective and its influence on the covariance matrix of measurement noise. In return, this would yield more accurate poses of the V2X objects transmitted to the ego-vehicle and better results especially regarding the calculated covariance matrix of the estimation error.

Once we obtain 3D pose estimations from an appropriate CNN approach, we can incorporate the following Kalman Filter approach for the above-mentioned tracking concept. The state vector of the road vehicle is composed of position x_1, x_2, heading h and speed v. The state transition equation can be expressed as follows:

$$\boldsymbol{x}(k) = \begin{bmatrix} x_1(k) \\ x_2(k) \\ v(k) \\ h(k) \end{bmatrix} = f\big(\boldsymbol{x}(k-1)\big) + w(k) \qquad \textbf{(1)}$$

Regarding the first derivatives in time of velocity and heading as process noise this equation can be written as:

$$\boldsymbol{x}(k) = \begin{bmatrix} x_1(k-1) + Ts(k-1)\cos h(k-1) \\ x_2(k-1) + Ts(k-1)\sin h(k-1) \\ v(k-1) \\ h(k-1) \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ T & 0 \\ 0 & T \end{bmatrix} \begin{bmatrix} \dot{v} \\ \dot{h} \end{bmatrix} \quad \textbf{(2)}$$

The measurement equation is defined as follows:

$$\boldsymbol{z}(k) = \boldsymbol{H}(k)\boldsymbol{x}(k) + \boldsymbol{v}(k) \quad \textbf{(3)}$$

When using a convolutional neural network for pose estimation, the measurement vector is as follows:

$$\boldsymbol{z}(k) = \begin{bmatrix} x_1 \\ x_2 \\ h \end{bmatrix} \quad \textbf{(4)}$$

The observation matrix $\boldsymbol{H}(k)$ expresses the projection between state changes and observed position changes of the detected vehicle in the camera plane and $\boldsymbol{v}(k)$ is the current amplitude of the measurement noise signal. The measurement noise can be assumed as zero mean normally distributed, isotropic and constant Figure 38. The observation matrix, however, is dependent on the position of the observed vehicle. The zero mean normally distributed non-isotropic and non-constant Figure 39. A Kalman Filter computes the optimal state estimate and the covariance matrix of the estimation error in this situation.

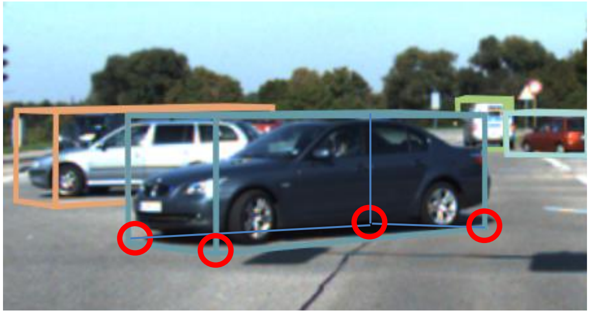


Figure 38: $\boldsymbol{v}(\boldsymbol{k})$ in the camera plane adapted from [76]

The output of the Kalman Filter is an optimal state estimation vector and the covariance matrix of the estimation error. Both needs to be transformed into world coordinates for compatibility with the coordinate system of the receiving car. While this transformation is straightforward for the state vector, transformation of the covariance matrix is not. All covariances of $h(k)$ and $v(k)$ with respect to the other elements of the state vector are zero. The covariances of the transformed to world positions x_1^w and x_2^w are calculated as follows:

$$cov(\boldsymbol{x}^{\boldsymbol{w}}(k)) = \boldsymbol{R}\, cov(\boldsymbol{x}(k))\boldsymbol{R}^T \quad \textbf{(5),}$$

where:

$$\boldsymbol{R} = \begin{bmatrix} \cos h & -\sin h \\ \sin h & \cos h \end{bmatrix} \quad \textbf{(6).}$$

This means, that for camera based infrastructure CPM messages, there is no need to transmit the whole covariance matrix. The diagonal elements and the position covariances added are sufficient. All calculations, however, execute in the roadside unit, because intrinsic and extrinsic camera calibration parameters are available there.

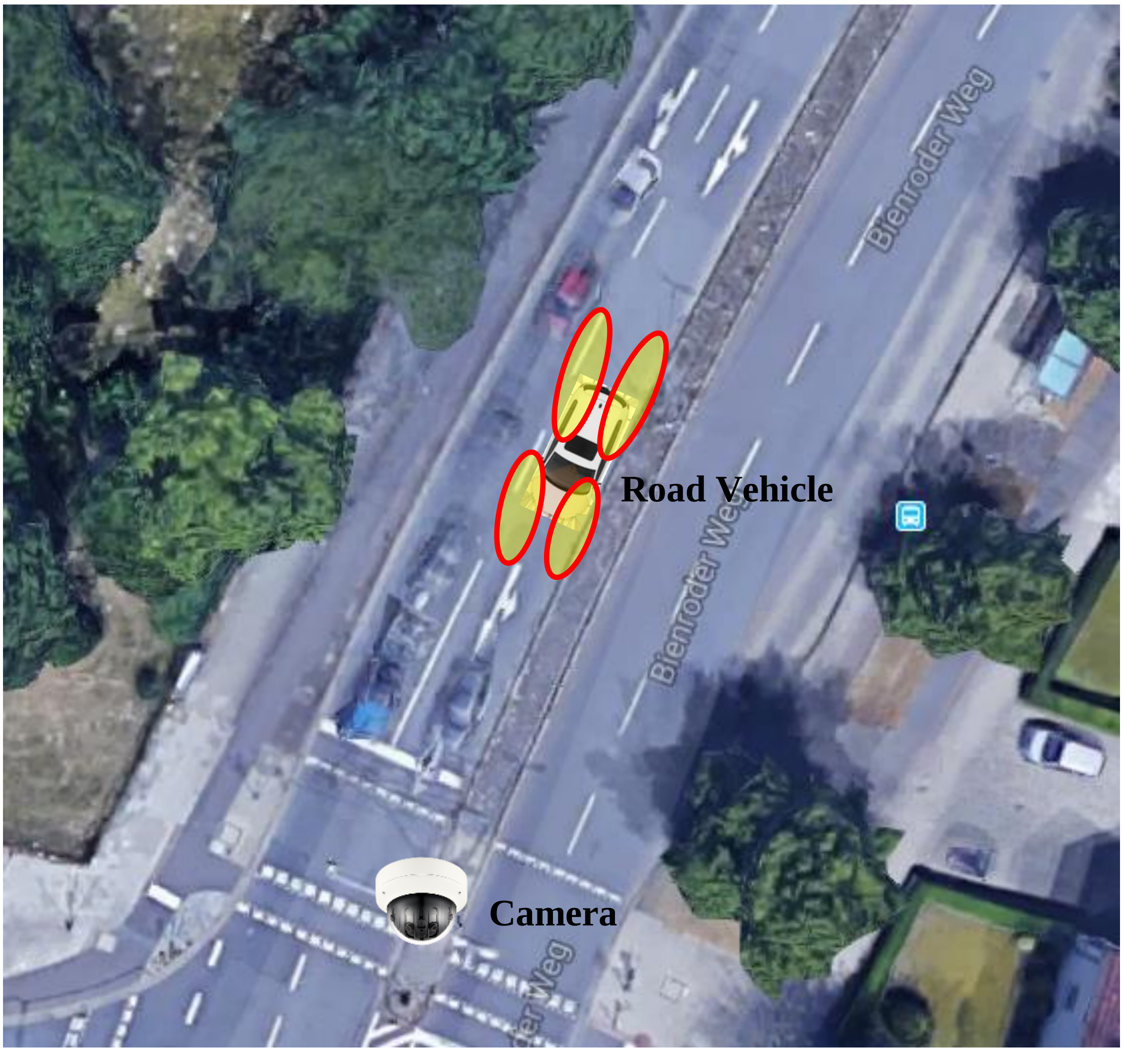


Figure 39: $v(k)$ in the coordinate system of $x(k)$

Inaccuracies in the pose estimation of V2X objects and the localization of the ego-vehicle inevitably lead to added deviations of the objects received via V2X. This necessitates the pose estimation and localization to be as accurate as possible and the association module to handle the remaining deviations. This is especially critical for multiple objects with similar dynamics in close proximity to each other e.g. vehicles waiting in multiple lanes next to each other at a traffic light. Once objects are wrongly associated, they cannot be fused correctly afterwards. Therefore, it is vital to associate the correct objects with each other. One aid for a correct association is to also incorporating the object history into the association algorithm.

Figure 40 shows an exemplary result of the association and fusion algorithm for LIDAR and CPM messages in the vehicle. In this image, the green boxes show the CPM messages, while the yellow boxes show the LIDAR messages. The time delay as well as an offset from the localization and the projection is visible in this data. Therefore, the fused result shown as a red box shows the greater truth towards the LIDAR messages regarding position, and a greater influence of the CPM messages regarding their size.

Figure 40: Fusion result (red boxes) between lidar (yellow boxes) and CPM (green boxes)

Once associated the objects are subsequently fused by deploying the covariance intersection algorithm [72]. Covariance intersection computes an optimal estimate of the real state of an object given state estimates and covariance matrices of the estimation error of those state estimates. It is reasonable to apply covariance intersection for cooperative perception [73]. Objects that cannot be associated naturally cannot be fused, but will be added to the global track list, as they might extend the view of the vehicle perception. The accuracy of those unfused tracks can be validated by considering the deviations between associated objects. Finally, the entire object-level fusion module outputs a global track list containing all objects perceived by the vehicle and the road site unit, where objects in the overlapping field of view are fused.

2.3.2 Analysing the impact of Cooperative Sensing for different Market Penetration Rates (MPR)

Connected and Automated Vehicles (CAVs) could improve their perception by exchanging CPMs using wireless technologies. This perception could be impacted by the number of connected vehicles presented in the environment that shares the sensor information. During early Market Penetration Rates (MPR), there will be less traffic participants sharing information about the environment so it could be difficult to achive higher levels of enviornmental pereption. Whereas at high MPR, there will be a high number of participants sharing similar information which could increase the unnecessary redundancy in the network and hence, there is a higher risk of saturating the communications channel. Therefore, it is important to investigate the impact of different MPR in the performance of cooperative sensing. To this aim, the performance and efficiency of the collective perception dynamic message generation rules (dynamic policy) defined in the ETSI collective perception service (see Section 2.1.2.1.3) is analysed with different percentage of MPR. The considered simulation set-up described in Section 2.2.2 and the performance of different MPR is analysed for both low and high traffic densities. In addition, with the forward sensor configuration described in Section 2.2.2, a new sensor configuration is considered for this study. In the new configuration, vehicles are equipped with a single sensor with 150m range and a 360º FoV.

2.3.2.1 Operation

Before analysing the performance and efficiency of each CPM generation policy for each MPR, it is necessary to better understand their operation. Figure 41 represents the Probability Density Function (PDF) of the number of CPMs transmitted per second per vehicle for different MPR. The number of CPMs generated per vehicle depends on the number of detected vehicles (i.e. traffic density) and on their dynamics (e.g. an object is included in a CPM every 4m). Due to this fact, different MPR percentage has similar CPM generation rates for each traffic density although their impact in the channel load will be quite different as shown in Section 2.3.2.2. The increase in the CPM generation rate with the 360º sensor configuration is due to the higher object detection rate of the 360º sensor. When compared between traffic densities, the speed of the vehicles is higher for low traffic densities than for higher ones. As a result, the vehicles satisfy more frequently one of the three conditions specified in Section 2.1.2.1.3 for the dynamic CPM generation rules (i.e., absolute position changes by more than 4m; absolute speed changes by more than 0.5m/s; 1 second since the last CPM transmitted), and vehicles generate more CPMs per second at low densities than at high densities.

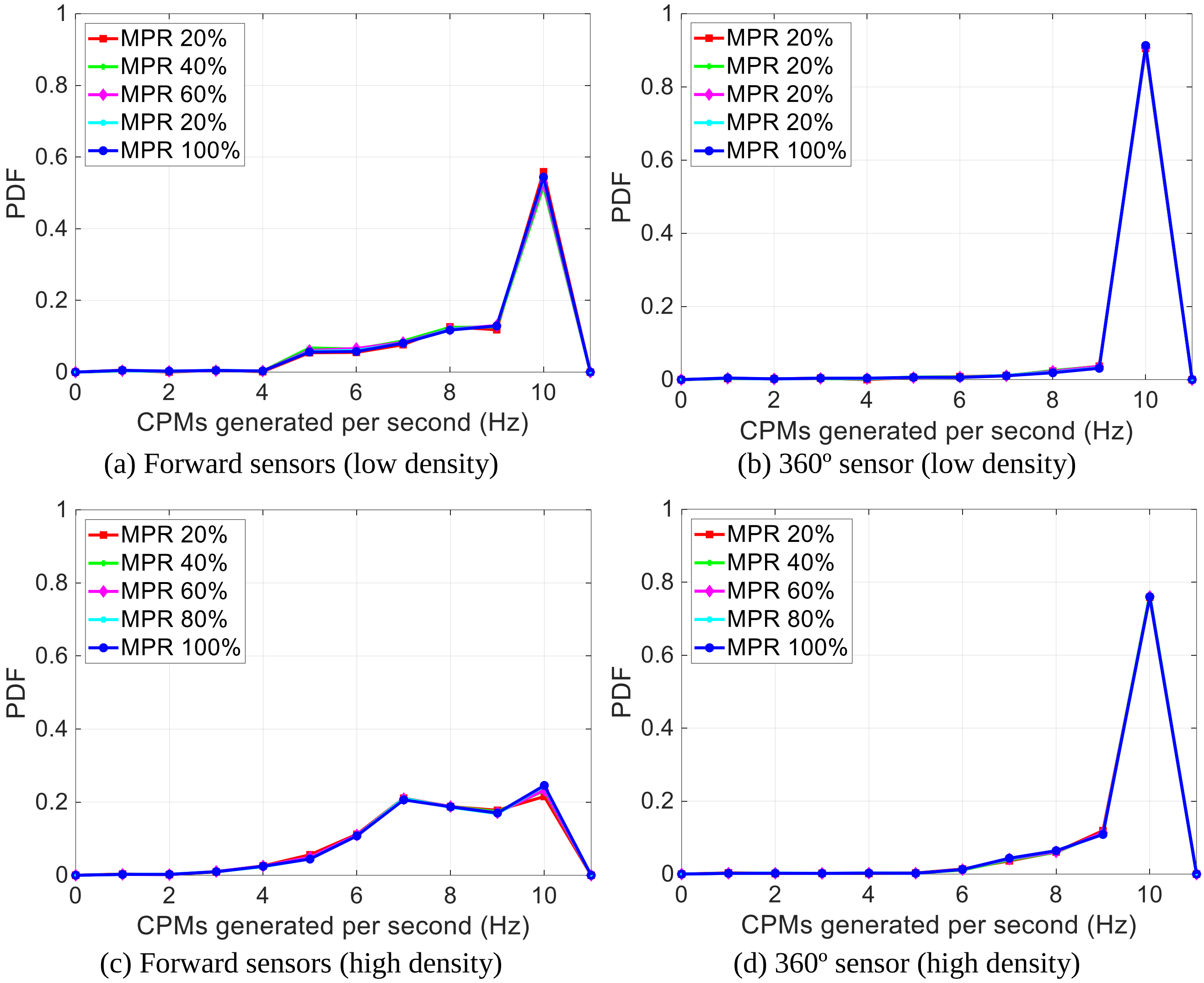
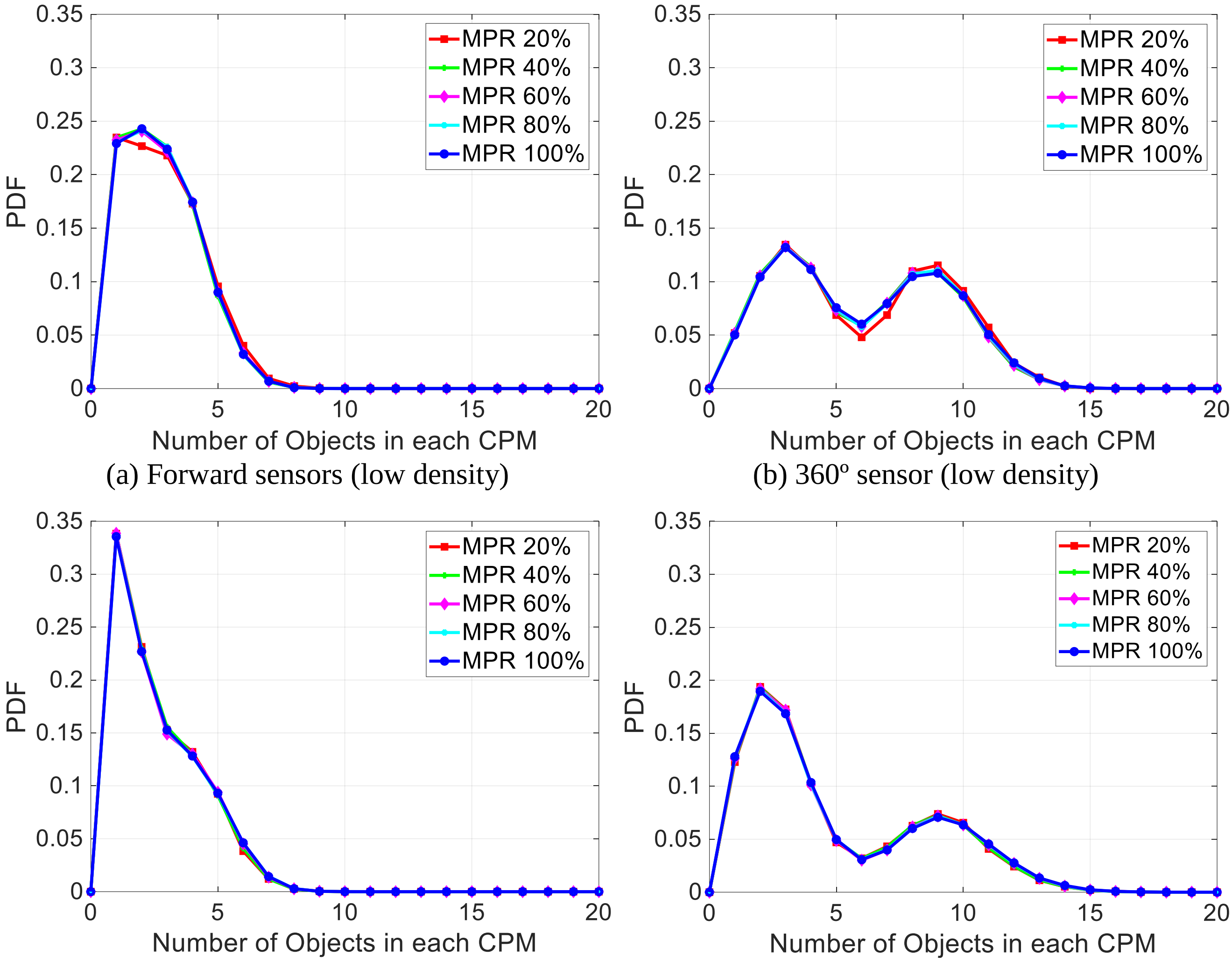


Figure 41. PDF (Probability Density Function) of the number of CPMs transmitted per second and per vehicle

Figure 42 represents the PDF of the number of objects included in each CPM for different MPR. Again, the increase in the objects included in each CPM with the 360º sensor configuration is due to the higher object detection rate of the 360º sensor. When comparing traffic densities, smaller CPMs with a smaller number of objects are generated in the high density scenario due to the lower travelling speed. Figure 41 and Figure 42 show that all MPR configurations have similar CPM generation rate and similar number of objects included in each CPM. However, the number of connected vehicles participating in cooperative sensing is different for each MPR configuration. To this aim, the network performance and the achieved perception is analysed further for different MPR.



(a) Forward sensors (low density)
(b) 360º sensor (low density)
(c) Forward sensors (high density)
(d) 360º sensor (high density)

Figure 42. PDF (Probability Density Function) of the number of objects included in each CPM

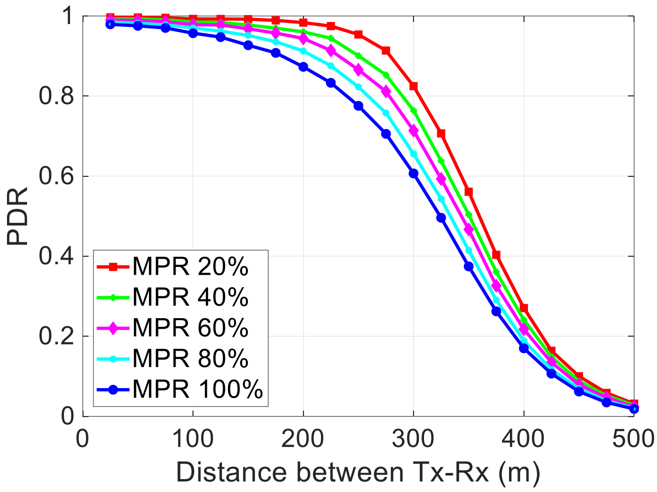
2.3.2.2 Communication Performance

This section evaluates the impact of the CPM generation policies on the communications performance. To this aim, Table 8 shows the average Channel Busy Ratio (CBR) experienced when implementing different MPR under the two traffic densities. The CBR is measured by each vehicle every second. The CBR is a measure of the channel load, and it is defined as the percentage of time that the channel is sensed as busy. A high CBR value indicates that the channel is very loaded and hence risks saturating. If this happens, the communications performance degrades and the packet delivery ratio decreases [49]. Table 8 shows that the channel load increases with the MPR. This is because with high MPR there are more connected vehicles in the network and generating CPMs which increases the channel load. The CBR increases with the traffic density is due to the increase in the number of participants (i.e. vehicles) present in the network. The CBR increases with 360º sensor configuration is due to the increase in the number of detected objects and the CPM rate (see Figure 41 and Figure 42).

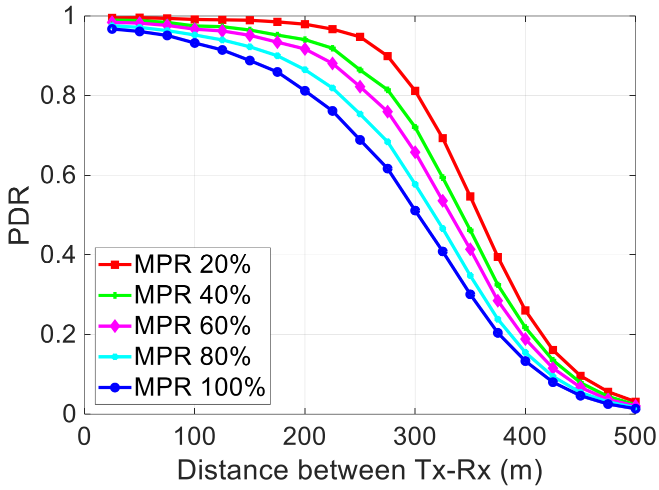
Table 8. Average CBR (Channel Busy Ratio)

MPR	Low density		High density	
	Forward sensors	**360º sensor**	**Forward sensors**	**360º sensor**
20%	3.34	4.89	7.83	11.69
40%	8.4	12.32	15.48	22.49
60%	11.74	17.11	20.19	29.12
80%	15.46	22.28	25.99	36.83
100%	19.29	27.57	31.8	44.44

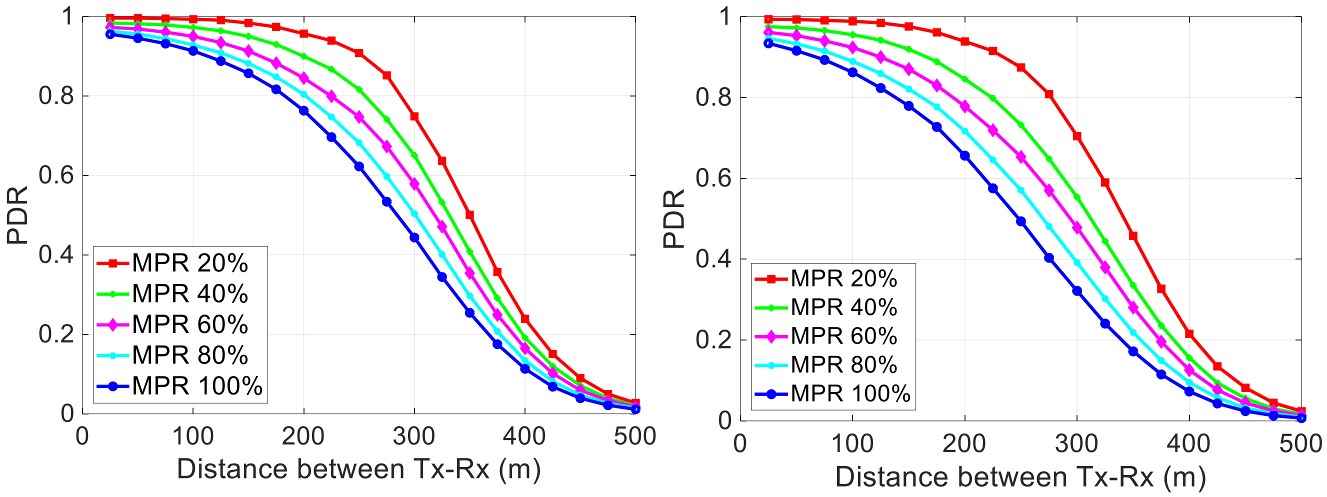
The channel load or CBR has an impact on the PDR (Packet Delivery Ratio). The PDR is defined as the probability of successfully receiving CPM as a function of the distance between the originating and receiving vehicles. Figure 43 plots the PDR of different MPR under the two traffic densities. The degradation of the PDR with the distance is due to the radio propagation effects. The PDR can also be degraded due to packet collisions or interference when the channel load is high. This effect is highlighted in Figure 43 where the PDR decreases as the MPR increases due to an increase in the channel load and packet collisions. Table 8 already showed how the channel load increases with the traffic density. The resulting PDR degradation observed in Figure 43 is a consequence of the trends observed in Table 8. Following these trends, Figure 43 shows that the MPR 20% achieves the highest PDR and the MPR 100% the lowest one. However, it is yet to be seen the collective perception levels achievables with low MPRs.



(a) Forward sensors (low density)



(b) 360º sensor (low density)



(c) Forward sensors (high density) (d) 360º sensor (high density)

Figure 43. PDR (Packet Delivery Ratio) as a function of the distance between transmitter and receiver

2.3.2.3 Perception capabilities

This section analyses the perception capabilities of vehicles for different MPR configurations. It is important to select an appropriate time window for analysis perception capabilities. Figure 44 plots the time required by ETSI CPM generation rules to send an update about an object for the given *T_GenCpm=0.1s* which is depicted as a function of object speed (m/s).

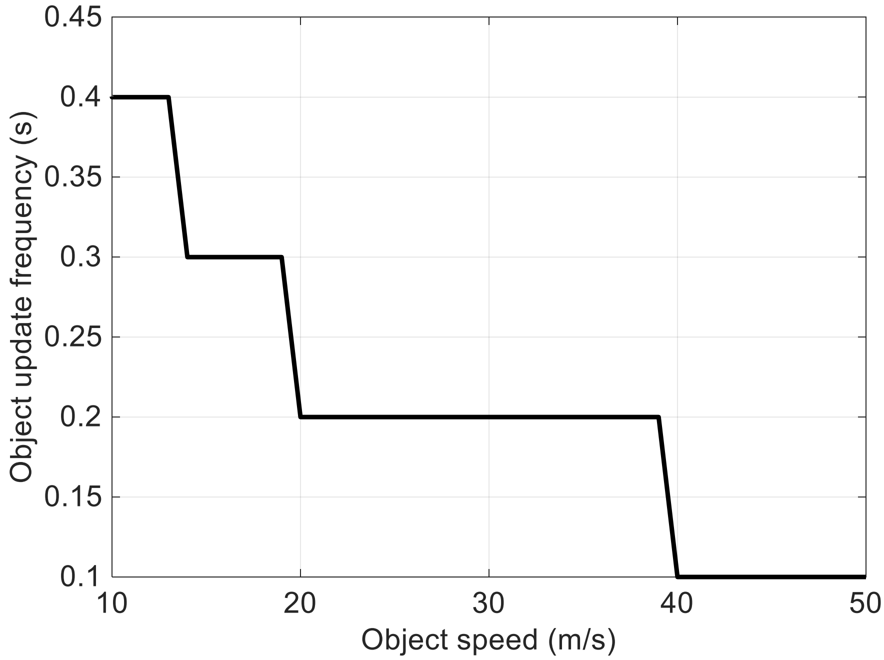
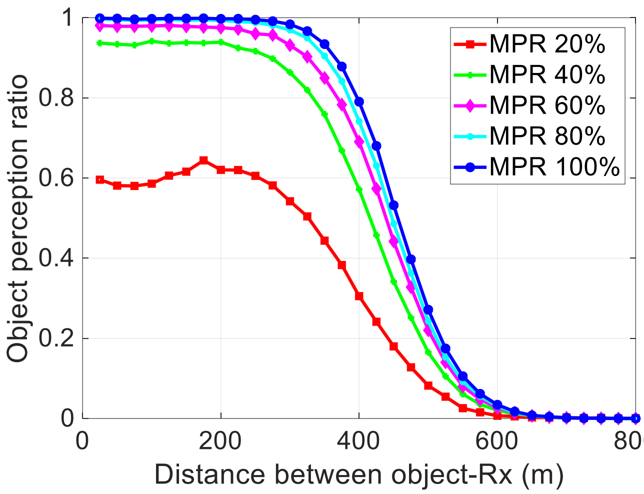


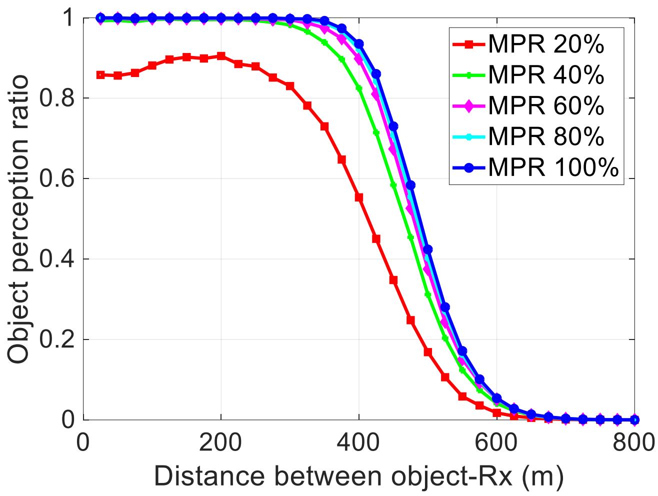
Figure 44. The estimated time required by ETSI CPM generation rules to send an update about an object for the given *TGenCPM=0.1s.*

Figure 44 shows that ETSI CPM generation rules include information about a vehicle in a CPM every 200ms for objects travelling between 20m/s and 40m/s and every 300ms for objects travelling between 14m/s to 19m/s for the selected *TGenCPM=0.1s*. For example, vehicles move at speeds between 32.7m/s and 38.8m/s in the low traffic density scenario (see Section 2.2.2). Vehicles then need 0.11s to 0.13s to move 4m. *T_GenCpm* is defined as a multiple of 100ms. Therefore, the information about a vehicle is included in a CPM every 200ms for low traffic densities. Similar calculations can be done for the high traffic density scenario. These calculations are important to select the adequate observation time window and correctly evaluate the performance and effectiveness of the collective perception service. From the analysis, the observation time windows of 200ms and 300ms for the low and high traffic density scenarios are considered respectively.

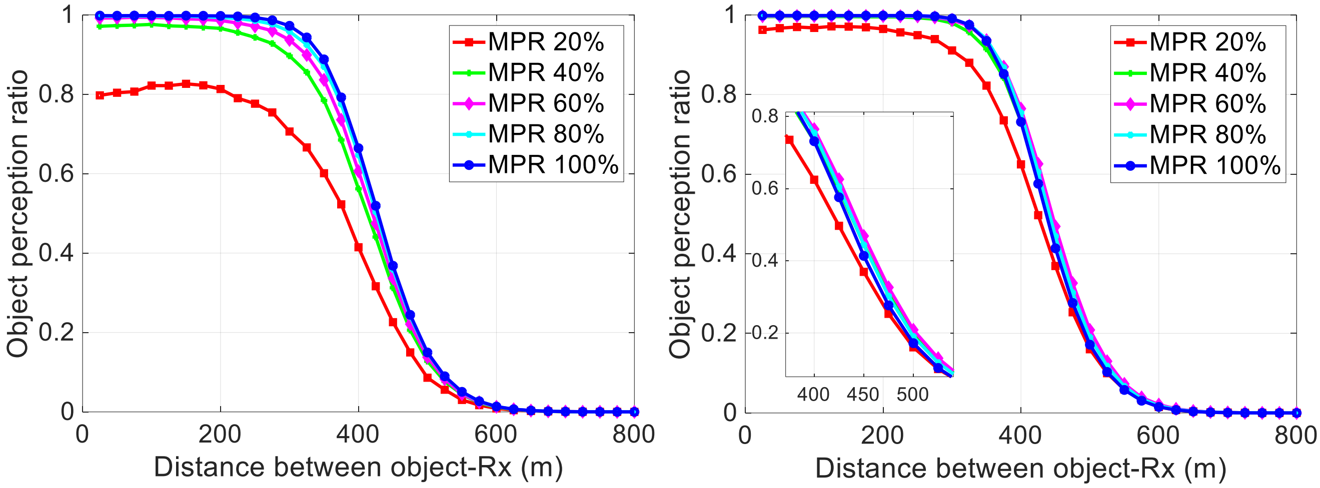
To this aim, we define the Object Perception Ratio as the probability to detect an object (vehicle in this study) through the reception of a CPM with its information in the selected time window. We consider that an object is successfully detected by a vehicle if it receives at least one CPM with information about that object within the selected time window. Figure 45 depicts the average Object Perception Ratio as a function of the distance between the detected object and the vehicle receiving the CPM for different MPR. Figure 45 shows that 20% of MPR achieves lower perception when compared with higher MPR. This is because the number of connected vehicles present in the environment that send CPM is not enough to perceive all the objects present in the environment. From MPR 40%, the perception tends to increase significantly and achieves higher perception for critical short distances (e.g. up to 200m). In particular, the 100% of MPR achieves the maximum perception at higher distances (e.g. beyond 200m) when compared with lower MPR. The degradation of perception at high distances is due to low PDR levels. If we compare different sensor configurations, the 360º sensor configuration achieves higher perception even for low MPR and this is due to the higher object detection rate of the sensor. In particular, at high traffic density all MPR configuration achieve perceptions higher than 95% for critical short distances (e.g. up to 200m). The subplot zoom shown in Figure 45.d depicts that the MPR 60% and MPR 80% perform better than the MPR 100% at higher distances and this is because of the lower PDR levels observed for MPR 100% (see Figure 43). The obtained results from Figure 45 show that higher percentage of MRP can generate non-negligible channel load levels that can degrade the communications performance and impact the network's scalability. It is hence necessary to evaluate whether the current CPM generation policies generate unnecessary redundancy about the detected objects for different MPR.



(a) Forward sensors (low density)



(b) 360º sensor (low density)

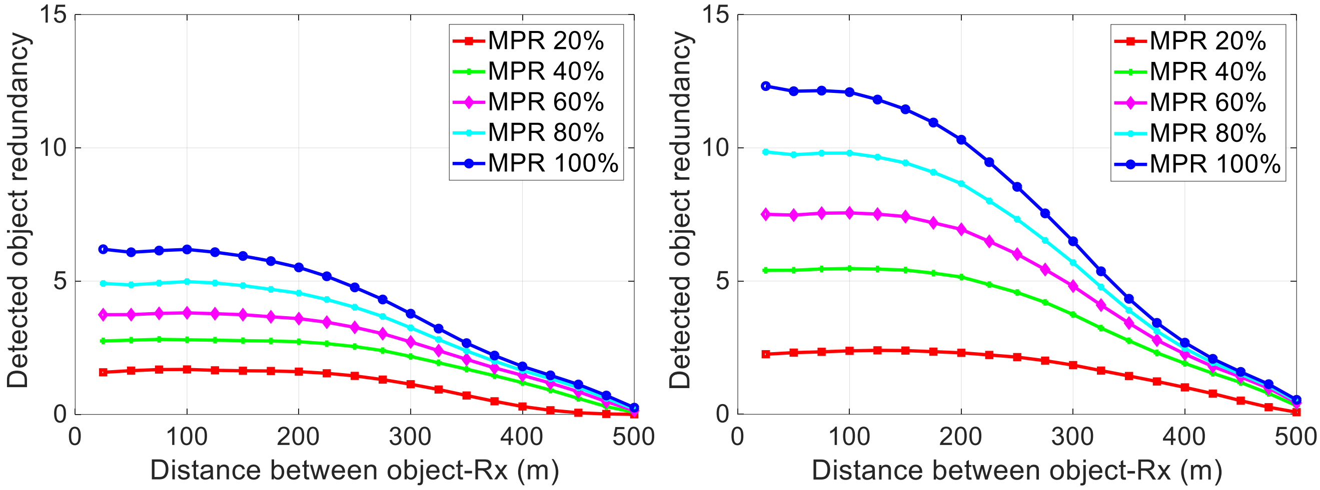


(c) Forward sensors (high density)

(d) 360º sensor (high density)

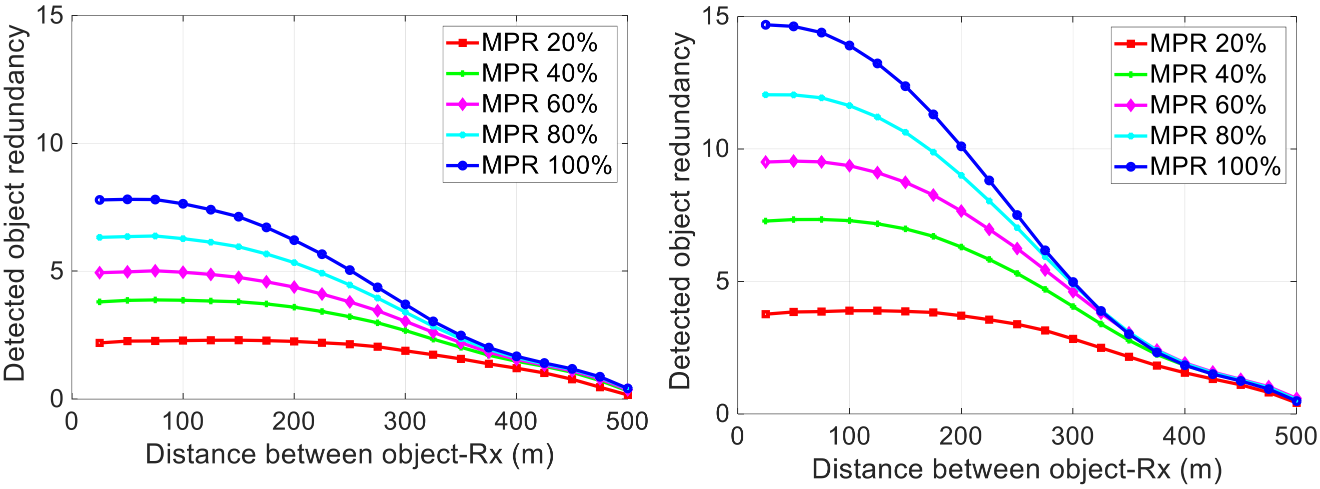
Figure 45. Object Perception Ratio as a function of the distance between the detected object and the vehicle receiving the CPM

Figure 46 illustrates the number of updates about the same object received under the selected time window. This metric is referred to as detected object redundancy and is depicted in Figure 46 as a function of the distance between the object and the vehicle receiving the CPM. The increase in the redundancy with the 360º sensor configuration is due to the increase in the object detection rate. The degradation observed in Figure 46 with the distance is a direct consequence of the PDR degradation reported in Figure 43. Figure 46 shows that an increase in the MPR, increases the redundancy in the network and the channel load and hence it increases the risk of saturating the channel (see Table 8). With lower MPR, the redundancy is reduced but not all objects in the environment are detected and reported due to less participants causing lower perception (see Figure 45). To achieve higher perception without generating unnecessary redundancy for higher MPR, the ETSI generation rules could be modified to further decrease the redundancy and increase the robustness and scalability of the vehicular network.



(a) Forward sensors (low density)

(b) 360º sensor (low density)



(c) Forward sensors (high density)   (d) 360º sensor (high density)

Figure 46. Detected object redundancy as a function of the distance between the detected object and the vehicle receiving the CPM.

2.3.3 TransAID proposals for improving Cooperative Sensing

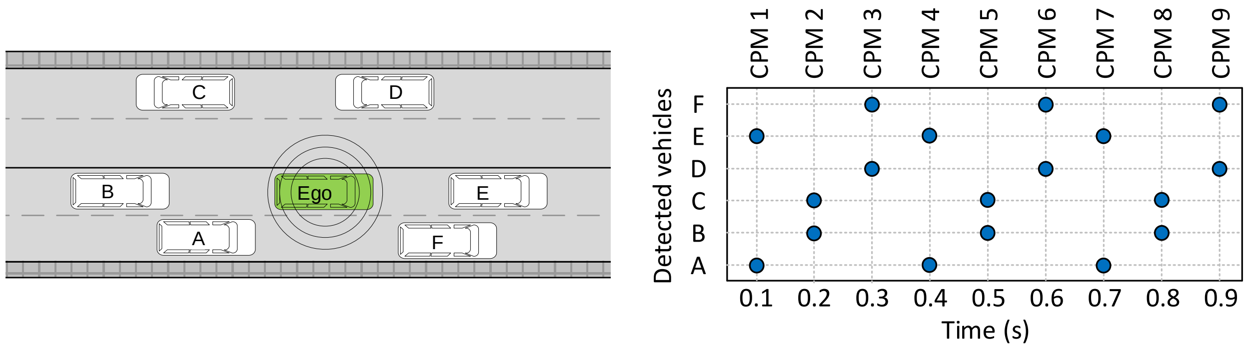
From the analysis performed in Section 2.2.2, it is concluded that the ETSI dynamic policy performs better than the periodic policy, however inefficiencies are identified in the dynamic policy and reported. In the following sections, TransAID addressed the inefficiencies in the dynamic policy by proposing two different algorithms. These algorithms have been presented at the ETSI's CPS (see Annex A and [34]).

2.3.3.1 Evolution of the message generation rules: Look-Ahead algorithm

The analysis performed in Section 2.2.2 showed that dynamic ETSI CPM generation rules (see Section 2.1.2.1.3) result in the frequent transmission of CPMs that include information about a small number of detected objects. This results in an inefficient use of the communication channel due to the frequent transmission of protocol headers and data about the transmitting vehicle (Figure 20). These inefficiencies reduce the probability of receiving CPM messages, and therefore the effectiveness of cooperative perception. The proposed look-ahead algorithm tackles these inefficiencies by modifying the current ETSI CPM generation rules so that less CPMs are transmitted and each CPM includes data about a higher number of detected objects. This study demonstrates that the proposed solution improves the reliability of V2X communications and the perception capabilities of CAVs compared to the current ETSI CPS implementation.

2.3.3.1.1 Motivation

We first highlight the limitations of the current ETSI CPM generation rules to motivate our proposal. Without loss of generality, we consider a highway scenario (Figure 47.a) whether ego vehicle is equipped with a sensor that has a Field of View (FoV) of 360º. The vehicle generates CPMs following the current dynamic ETSI CPM generation rules and checks the conditions to generate a CPM every *T_GenCpm*=0.1s. Let's first consider that all vehicles in the scenario move at 70km/h (19.4 m/s). In this case, all vehicles detected by the ego vehicle satisfy condition 1 described in Section 2.1.2.1.3 every 205ms. The ego vehicle then includes each detected vehicle in a CPM every 300ms. Let's suppose an ideal scenario where the ego vehicle detects all neighbouring vehicles in Figure 47.a at the same time. The ego vehicle generates then 3 CPMs per second, and each CPM includes the information of the 6 detected vehicles. It is though very unlikely that an ego vehicle can detect all its neighbouring vehicles at the same time. In a realistic scenario, vehicles constantly enter and leave the detection range of the ego vehicle at different times. The ego vehicle will then include the detected objects (i.e. vehicles in this study) in different CPMs as illustrated in Figure 47.b. This figure illustrates an example in which the ego vehicle detects neighbouring vehicles at different times. In particular, the figure represents a scenario in which the ego vehicle detects two different neighbouring vehicles every *T_GenCpm*=0.1s. In this case, the ego vehicle ends up transmitting 9 CPMs per second instead of 3 like in the ideal scenario. Each CPM includes now information about two detected objects instead of six, as in the ideal scenario where all vehicles were detected at the same time. Transmitting more CPMs per second consumes more bandwidth since each CPM includes the ITS PDU Header, and the Management and Station Data containers of the ego vehicle (Section 2.1.2.1.2). In addition, each CPM implies additional protocol headers from the Transport, Network, MAC (Medium Access Control) and PHY (Physical) layers. A similar effect is observed if we consider a scenario where vehicles move at different speeds. The ego vehicle still checks the conditions to generate a CPM every *T_GenCpm*=0.1s. However, since each vehicle moves at different speeds, they satisfy condition 1 in Section 2.1.2.1.3 at different time instants, and the ego vehicle will include their data in different CPMs. This can again result in the frequent transmission of CPMs with data about a small number of detected objects. We have analysed and quantified this trend by means of simulations using the network simulator NS-3 and the road mobility simulator SUMO.

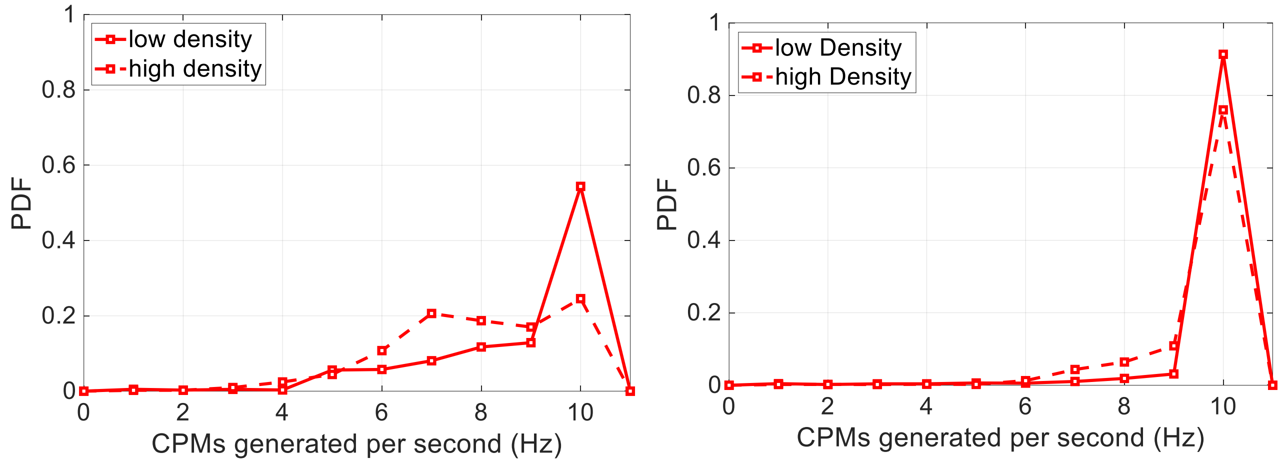


(a) Highway scenario

(b) Detected vehicles included per CPM

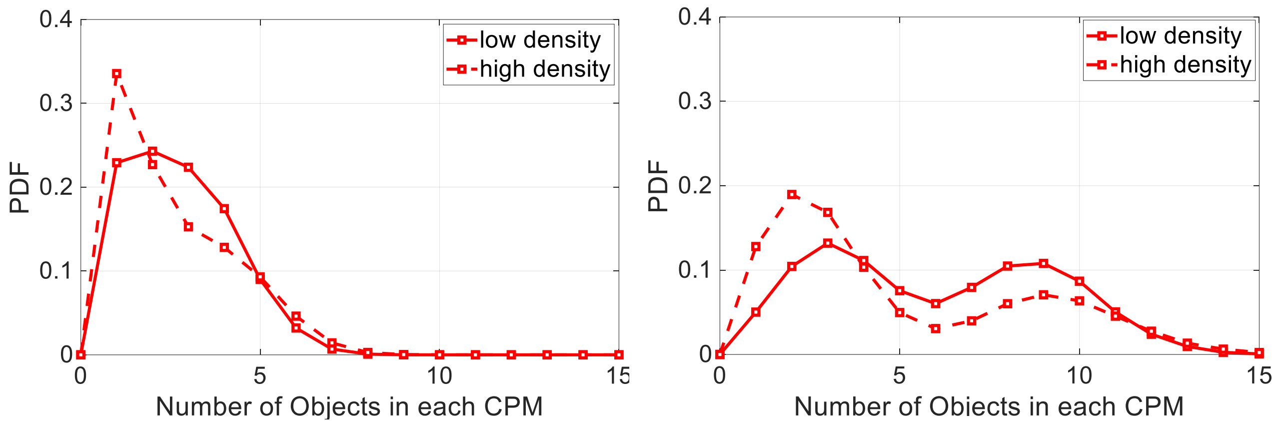
Figure 47. Example to motivate our proposed solution.

Simulations have been conducted following the scenarios and network configuration defined in Section 2.2.2. In addition to the previous forward sensor configuration, a new 360º sensor configuration is incorporated in this study. In the 360º sensor configuration, vehicles are equipped with a single sensor with 150m range and a 360º FoV. Figure 48 depicts the Probability Density Function (PDF) of the number of CPMs generated per vehicle per second. Figure 49 represents the PDF of the number of detected objects included in each CPM. Both figures are obtained using the current ETSI CPM generation rules for different sensor configurations. Figure 48 clearly shows that the current rules result in that CPMs are mostly generated every 0.1s (i.e. at 10Hz) independently of the sensor configuration and traffic density. These CPMs contain information about a small number of detected objects (Figure 49) in each CPM. The number of objects included per CPM is actually smaller than the total number of detected objects per vehicle. This is actually visible when comparing Figure 49 with Figure 50 that represents the PDF of the total number of detected objects per vehicle. As stated, the transmission of frequent and small CPM messages adds significant channel overhead. All this overhead increases the channel load and can reduce the reliability of V2X communications. This can impinge the exchange of CPM messages and reduce the perception of CAVs. This study proposes a novel algorithm that modifies the ETSI CPM message generation rules. The algorithm is designed to avoid the frequent transmission of CPMs with a small number of detected objects, and ultimately improve the perception of CAVs.



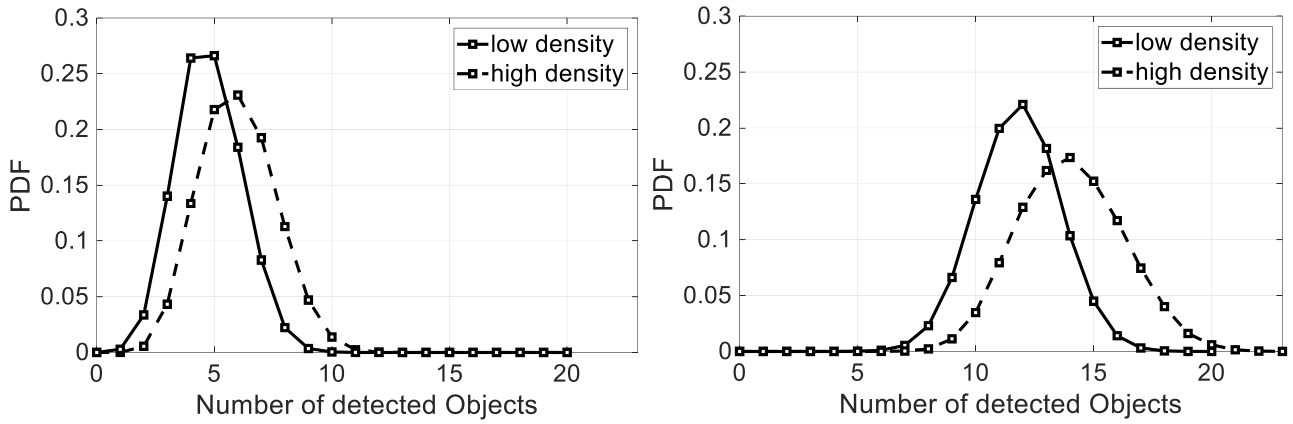
(a) Forward sensors (b) 360º sensor

Figure 48. PDF (Probability Density Function) of the number of CPMs generated per vehicle per second.



(a) Forward sensors (b) 360º sensor

Figure 49. PDF (Probability Density Function) of the number of detected objects included in each CPM.



(a) Forward sensors (b) 360º sensor

Figure 50. PDF (Probability Density Function) of the number of detected objects per vehicle.

2.3.3.1.2 Proposed Look-Ahead Mechanism

The algorithm is designed to improve the perception or sensing capabilities of CAVs compared to the current ETSI CPM proposal. The algorithm is based on the current ETSI CPM generation rules. In particular, vehicles check the conditions to generate a new CPM every *T_GenCpm*. The algorithm computes for each detected object the variation of absolute position (ΔP), the variation of speed (ΔS) and the time elapsed (ΔT) since the last time the detected object was included in a CPM. A new CPM is generated if at least one of the conditions specified in section 2.1.2.1.3 is satisfied following the current ETSI CPM generation rules. If it is the case, the CPM must include the information about the detected objects that satisfy ΔP>4m or ΔS>0.5m/s or ΔT>1s. The pseudo-code for this process is reported in lines 1-8 of Algorithm I.

The algorithm extends the ETSI CPM generation rules as follows. The algorithm estimates every time a new CPM must be generated (following the ETSI CPM generation rules) if any of the detected objects that are not included in this new CPM would be included in the next CPM if their current speed and acceleration was maintained. To this aim, the algorithm estimates the following parameters:

$$Next\ \Delta P = \Delta P + S \cdot T\_GenCpm \qquad (1)$$

$$Next\ \Delta S = \Delta S + A \cdot T\_GenCpm \qquad (2)$$

$$Next\ \Delta T = \Delta T + T\_GenCpm \qquad (3)$$

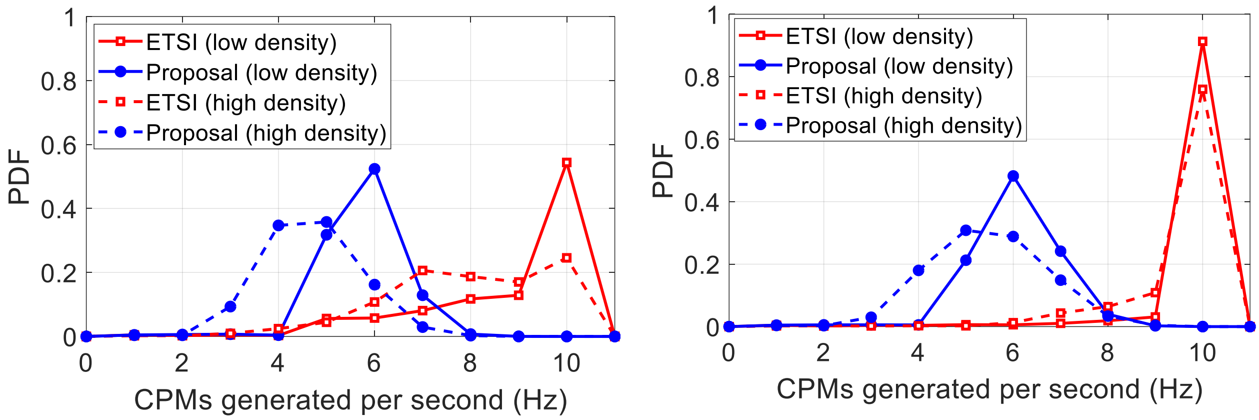
where *S* and *A* are the current speed and acceleration of the detected object. The algorithm includes in the current CPM those detected objects that satisfy *Next* ΔP>4m or *Next* ΔS>0.5m/s or *Next* ΔT>1s. Their information (ΔP, ΔS and ΔT) is transmitted in the current CPM instead of the next CPM. Anticipating the transmission of their information is proposed to avoid transmitting many CPMs with information about a small number of detected objects. The following section demonstrates that this approach actually improves the perception compared to the current ETSI implementation (dynamic policy). The pseudo-code of the proposed extension to the ETSI CPM generation rules is described in lines 9-16 of Algorithm I.

ALGORITHM I.
Input: Detected objects
Output: Objects (if any) to include in CPM
Execution: Every *T_GenCpm*

1. Set *flag* = false
2. **For** every detected object **do**
3.   Calculate ΔP, ΔS and ΔT since the last time included in a CPM
4.   **If** ΔP>4m || ΔS>0.5m/s || ΔT>1s **then**
5.   Include object in current CPM
6.   Set *flag* = true
7.   **End If**
8. **End For**
9. **If** *flag* = true **then**
10.   **For** every detected object not included in current CPM **do**
11.   Calculate *Next* ΔP, *Next* ΔS and *Next* ΔT
12.   **If** *Next* ΔP>4m ‖ *Next* ΔS>0.5m/s ‖ *Next* ΔT>1s **then**
13.   Include object in current CPM
14.   **End if**
15.   **End For**
16. **End If**

2.3.3.1.3 Evaluation

The performance of the proposed algorithm is analysed using the simulation set-up defined in Section 2.2.2. We consider that *T_GenCpm*=0.1s, and analyse the performance for both low and high traffic densities and the forward and 360º sensor configurations. Figure 51 compares the PDF of the number of CPMs generated per vehicle per second with the ETSI CPM generation rules and with the proposal. The results obtained show that the proposed algorithm significantly reduces the number of CPMs generated per second compared to the current ETSI rules. This reduction is achieved for all traffic densities and sensors' configuration. Table 9 shows that the proposal reduces the average number of CPMs generated per vehicle and per second by 34%-43% compared to the current ETSI implementation.



(a) Forward sensors (b) 360º sensor

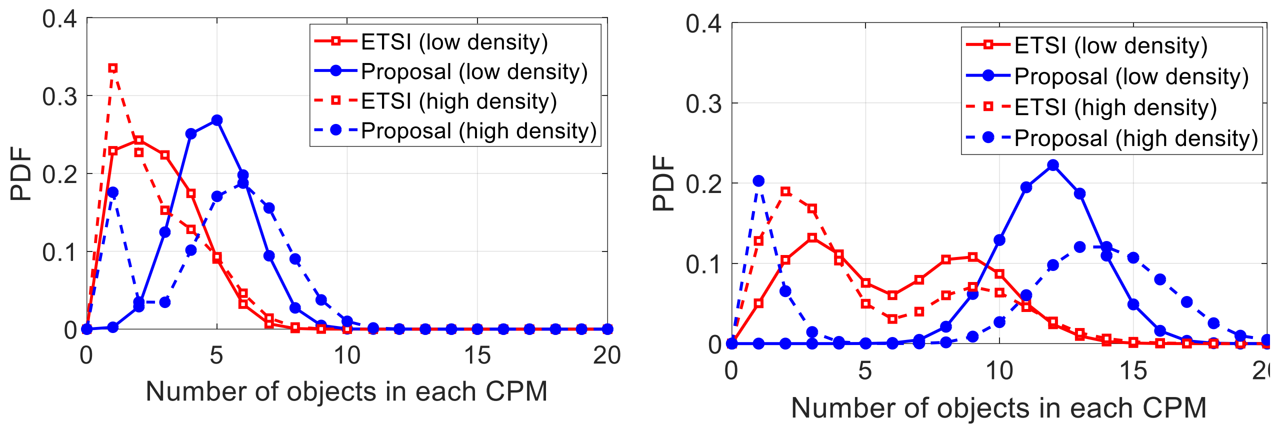
Figure 51. PDF (Probability Density Function) of the number of CPMs generated per vehicle per second.

Table 9. AVERAGE CPM RATE

Traffic Density	Policy	Forward sensors	360º sensor
Low	ETSI	8.7 Hz	9.7 Hz
	Proposal	5.7 Hz	6.0 Hz
	Difference	-34.5%	-38.1%
High	ETSI	7.9 Hz	9.5 Hz
	Proposal	4.6 Hz	5.4 Hz
	Difference	-41.7%	-43.2%

The proposal reduces the number of CPMs transmitted per second by increasing the number of detected objects included in each CPM. This is actually observed in Figure 52. This figure compares the PDF of the number of objects included in each CPM with ETSI's implementation and with the proposal. Figure 52 shows that the proposal increases the number of detected objects included per CPM and reduces the number of CPMs that only include information about 1 or 2 detected objects. Augmenting the sensors' field of view increases the number of detected objects per CPM since more objects can be detected. A similar effect is observed when the traffic density increases. However, when the traffic density increases, the detected objects need to be included in a

CPM less frequently since vehicles move at lower speeds. Figure 52 shows that the proposal only generates some CPMs with a small number of objects under high densities. These CPMs are generated when a vehicle detects for the first time new neighbouring vehicles.



(a) Forward sensors
(b) 360º sensor

Figure 52. PDF (Probability Density Function) of the number of detected objects included in each CPM.

The results reported so far clearly show that the proposal generates less CPMs per second than the current ETSI implementation. This is done by increasing the number of detected objects reported per CPM. Transmitting less CPMs per second reduces the number of channel access attempts and the number of times the ITS PDU header and the Management and Station Data containers of a vehicle are transmitted. This is visible in Table 10 that reports the average CPM bytes generated per second and per vehicle with ETSI's implementation and the proposal. The table also reports the difference of CPM bytes transmitted with the proposal compared to the current ETSI implementation. Table 10 shows that the proposal reduces the transmission of headers and containers related to the transmitting vehicle (referred to as HC in the table) by 34%-43% compared to the current ETSI implementation. On the other hand, the proposal augments the number of times a detected object is reported in a CPM (and hence the corresponding POC bytes) between 12% and 21% depending on the scenario. This increase results from the reorganization of how detected objects are reported in CPMs.

Despite this increase, Table 11 shows that the proposal reduces the channel load compared to the current ETSI implementation. The channel load is estimated in terms of the average CBR (Channel Busy Ratio) that is defined as the percentage of time that the channel is sensed as busy.

shows that the proposal reduces the CBR by 10%-23% compared to the ETSI implementation. These reduction levels are higher than the reduction of average total CPM bytes reported in Table 10. This is the case because transmitting less CPMs per second not only reduces the average CPM bytes transmitted per vehicle and per second (Table 10), but also the protocol headers generated by the lower layers when a packet is transmitted. This explains why our proposal achieves higher average CBR gains compared to the ETSI solution (Table 11) than gains in terms of average total CPM bytes (Table 10). Higher reduction levels are obtained with forward sensors because these sensors detect a lower number of objects. In this case, the Management, Station Data and Sensor Information containers represent a larger proportion of the total bits transmitted over the communication channel. Similarly, the proposal achieves higher CBR reduction levels compared to the ETSI implementation when the traffic density increases. This shows that the proposal has a positive impact on the scalability of vehicular networks.

Reducing the CBR and channel load reduces the packet collisions and improves the PDR (Packet Delivery Ratio). This is actually shown in Figure 53 and Table 12. Figure 53 plots the PDR of the

ETSI's implementation and the proposal. The figure shows that the proposal increases the PDR compared to the ETSI solution. Also, Table 12 reports the distance up to which a PDR equal or higher than 0.9 is guaranteed. Table 12 shows that the proposal increases this distance compared to the current ETSI CPM solution. The increase is around 9%-11% under low traffic density and 35% under high traffic density. These results demonstrate that the proposal increases the reliability of V2X communications.

Table 10. Average CPM bytes generated per second per vehicle

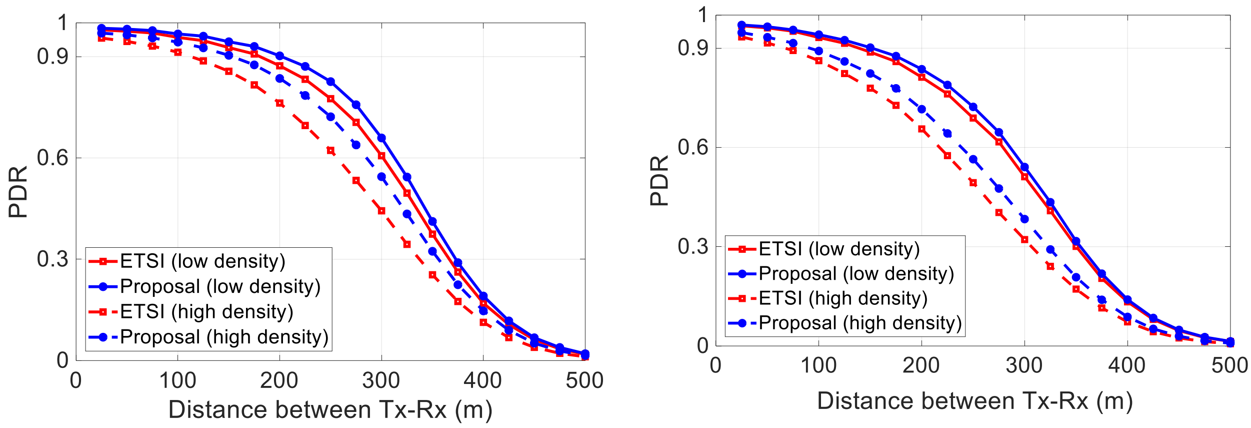
Traffic Density	Policy	Forward sensors				360º sensor			
		HC	SIC	POC	Total	HC	SIC	POC	Total
Low	ETSI	1055	35	855	1945	1179	35	2060	3275
	Proposal	697	35	990	1722	732	35	2501	3268
	Difference	-34%	0%	16%	-12%	-38%	0%	22%	-0.2%
High	ETSI	963	35	740	1738	1151	35	1673	2859
	Proposal	569	35	831	1434	657	35	1962	2654
	Difference	-41%	0%	12%	-18%	-43%	0%	17%	-7%

Table 11. Average CBR (Channel Busy Ratio)

Traffic Density	Policy	Forward sensors	360º sensor
Low	ETSI	19.3%	27.6%
	Proposal	15.6%	24.9%
	Difference	-19.2%	-9.8%
High	ETSI	31.8%	44.4%
	Proposal	24.4%	38.2%
	Difference	-23.3%	-14.0%

Table 12. Distance (meters) with PDR ≥ 0.9

Traffic Density	Policy	Forward sensors	360º sensor
Low	ETSI	181	139
	Proposal	202	152
	Difference	11.6%	9.4%
High	ETSI	113	67
	Proposal	153	91
	Difference	35.4%	35.8%

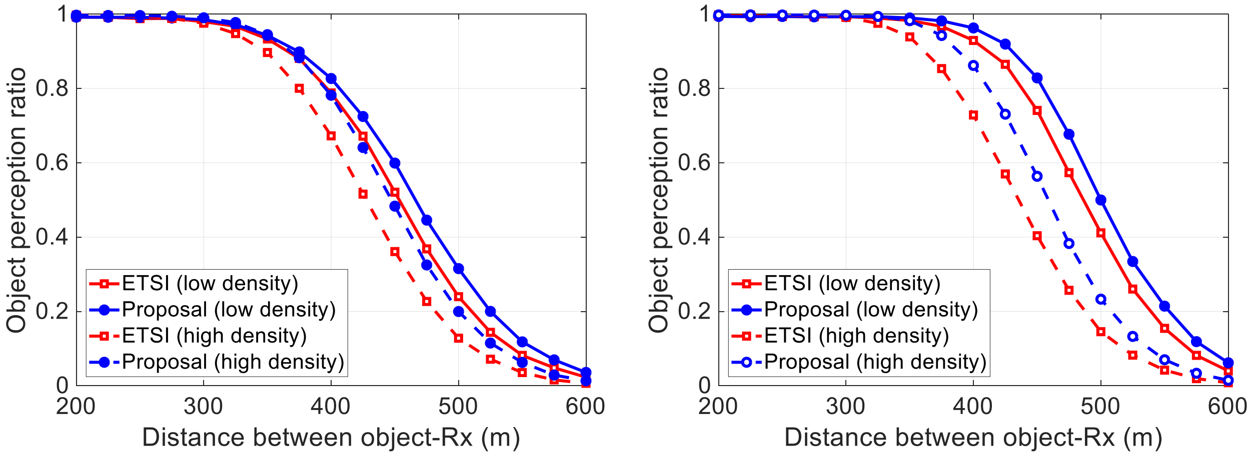


(a) Forward sensors (b) 360º sensor

Figure 53. PDR (Packet Delivery Ratio) as a function of distance between transmitter and receiver.

We also analyse the object perception ratio to demonstrate that the proposal also achieves higher perception capabilities of CAVs compared to the current ETSI implementation. The object perception ratio is defined as the probability to detect an object (i.e. vehicle in this study) in a given time window thanks to the exchange of CPMs. ETSI CPM generation rules include information about a vehicle in a CPM every 200ms and 300ms for the low and high traffic density scenarios respectively. We then consider observation time windows of 200ms and 300ms for the low and high traffic density scenarios based on the analysis reported from Figure 44. These values correspond to the time required by ETSI CPM generation rules for a vehicle to send an update about an object in a CPM for the two traffic densities. The CPMs can be transmitted by different vehicles in the scenario. Figure 54 plots the average object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPM. For each traffic density, Figure 54 shows that the proposal improves the object perception ratio compared to the current ETSI implementation. This is due to two main reasons. The first one is the fact that the proposal increases the PDR and therefore the probability to correctly receive CPM messages increases. The second reason is that the proposal reorganizes the transmission of detected objects in CPMs. This reorganization resulted in a lower number of transmitted CPMs and an increase (between 11% and 21%) in the average number of times that a detected object is reported in a CPM. This also has a positive impact on the perception capabilities of CAVs and hence on the object perception ratio.

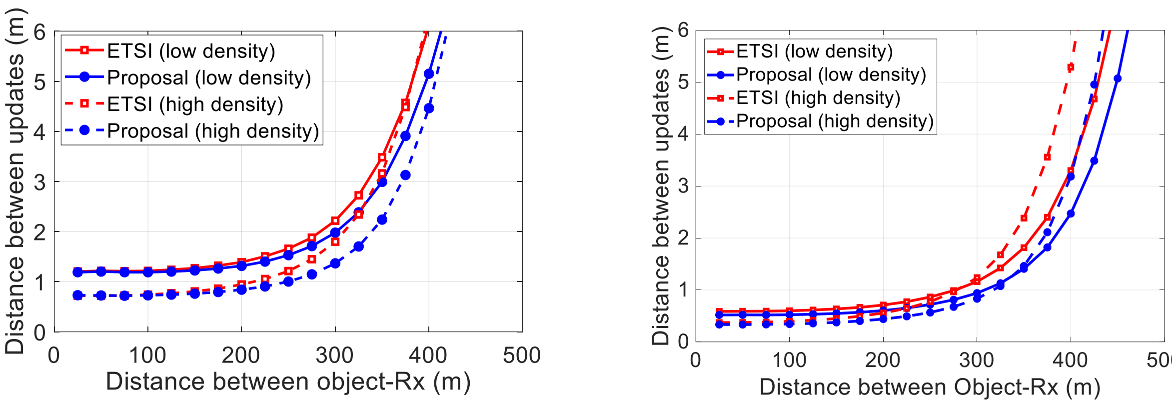
Figure 54 also shows that the object perception ratio decreases with the traffic density. This is the case because higher densities augment the channel load and reduce the PDR. In addition, vehicles move at lower speeds with high traffic densities, and their data is included less frequently in CPMs. The sensor capabilities also have an impact on the object perception ratio. Figure 54 shows that 360º sensors achieve a higher object perception ratio than forward sensors. This is due to the fact that more vehicles report about the same detected object when sensors have a larger FoV.



(a) Forward sensors (b) 360º sensor

Figure 54. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPM.

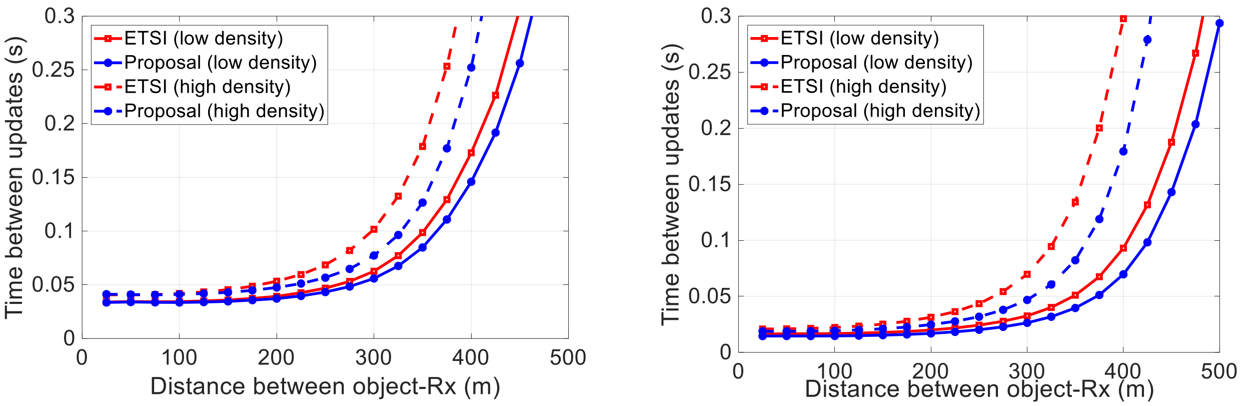
The perception achieved with the proposal is also analysed in terms of how often a vehicle receives updates about a detected object. The updates can be received from any neighbouring vehicle that has detected the same object. Figure 55 plots the average distance travelled by an object between updates as a function of the average distance between the object and the vehicle receiving the CPMs. The shortest the travelled distance the more frequent a vehicle receives updated information about a detected object. Figure 55 shows that the proposal and ETSI’s implementation can provide updates about detected objects every 4m (or less) up to distances between 350 and 400m. 4m is considered as a target reference following the ETSI CPM generation rules. Figure 55 also shows that the proposal generates updates about the detected objects at least as frequently as the current ETSI solution. In fact, the proposal generates more frequent updates for large distances between the detected object and the vehicle receiving the CPMs. This shows once more that the proposal improves the perception of CAVs compared to the current ETSI implementation.



(a) Forward sensors (b) 360º sensor

Figure 55. Average distance travelled by a detected object between updates received by a vehicle. Results are shown as a function of the average distance between the detected object and the vehicle receiving the CPMs.

Similar to Figure 55, Figure 56 plots the time difference between received CPMs with information about the same object or vehicle. The metric (referred to as the time between object updates) is represented as a function of the distance between the object and the vehicle receiving the CPMs. It is important to emphasize that the CPMs including information about the same object or vehicle might be transmitted by different or multiple vehicles. Figure 56 shows that the proposal and ETSI's implementation can provide object updates below 0.1s up to 300m approximately. For large distances, the proposal even performs better by generating more frequent updates between the detected object and the vehicle receiving the CPMs while better controlling the channel load (Table 11 and improving the communications performance (Table 12).



(a) Forward sensors (b) 360º sensor

Figure 56. Average time between object updates as a function of the distance between the detected object and the vehicle receiving the CPM.

2.3.3.2 Proposal for Redundancy Mitigation in Collective perception

The analysis performed in Section 2.2.2 showed that dynamic ETSI CPM generation rules (see Section 2.1.2.1.3) result in the frequent transmission of CPMs that include information about a small number of detected objects. This can compromise the network's scalability since most of the transmitted data are headers rather than data about detected objects. The analysis also showed that current CPM generation rules result in significant redundancy. For example, the study showed that vehicles can receive as much as 25 to 35 times per second the same data about a detected object under the evaluated scenarios (see Figure 24). This is the case because current CPM generation rules are exclusively based on changes of the detected objects' dynamics (position and speed). In this case, all vehicles in the vicinity of a detected object that detect a change in the objects' dynamics will generate a CPM with the same information about the detected object. Redundancy can be positive to confirm the accurate detection of objects or vehicles. However, an excessive redundancy can overload the V2X communications channel and compromise the network's scalability. It can also negatively impact the perception accuracy if an overloaded channel results in packet collisions. These collisions can reduce the probability of receiving CPM messages and ultimately impact the effectiveness of collective perception or cooperative sensing.

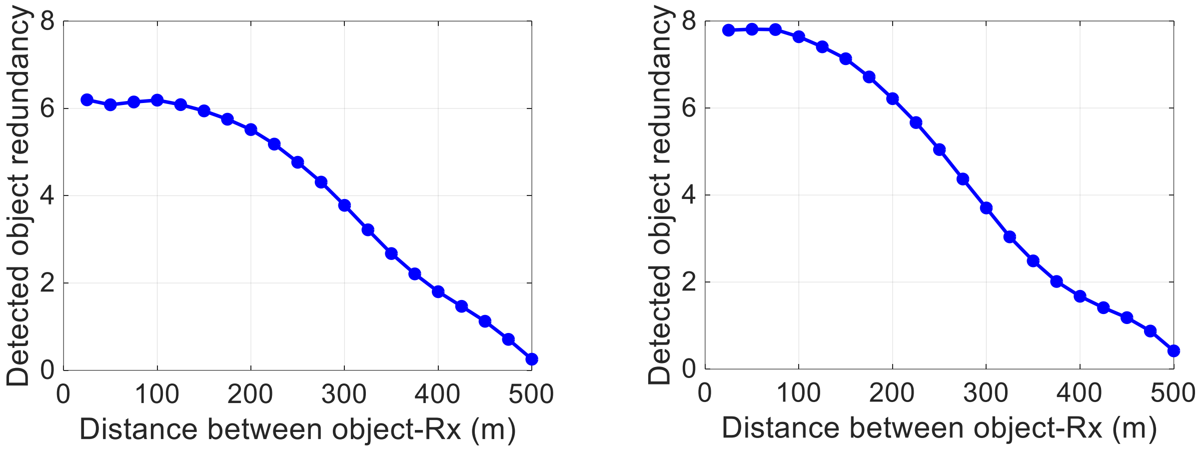
The proposed redundancy mitigation algorithm modifies the current ETSI CPS solution in order to control the redundancy in the network without degrading the perception capabilities of Connected and Automated Vehicles (CAVs). The proposal controls redundancy by preventing vehicles to report about detected objects in CPMs if they have already received updates about the same object from other vehicles. Transmitting another CPM with the same detected object data will increase redundancy without a significant benefit to neighbour vehicles that have already received the same data from other vehicles. The performance evaluation demonstrates that the proposed solution reduces significantly the redundancy in the network as well as the channel load and improves the

V2X reliability. In addition, the proposal maintains the perception achieved with the current ETSI solution for short and medium distances (up to around 200m radius). These distances are critical for the safety of CAVs.

2.3.3.2.1 Motivation

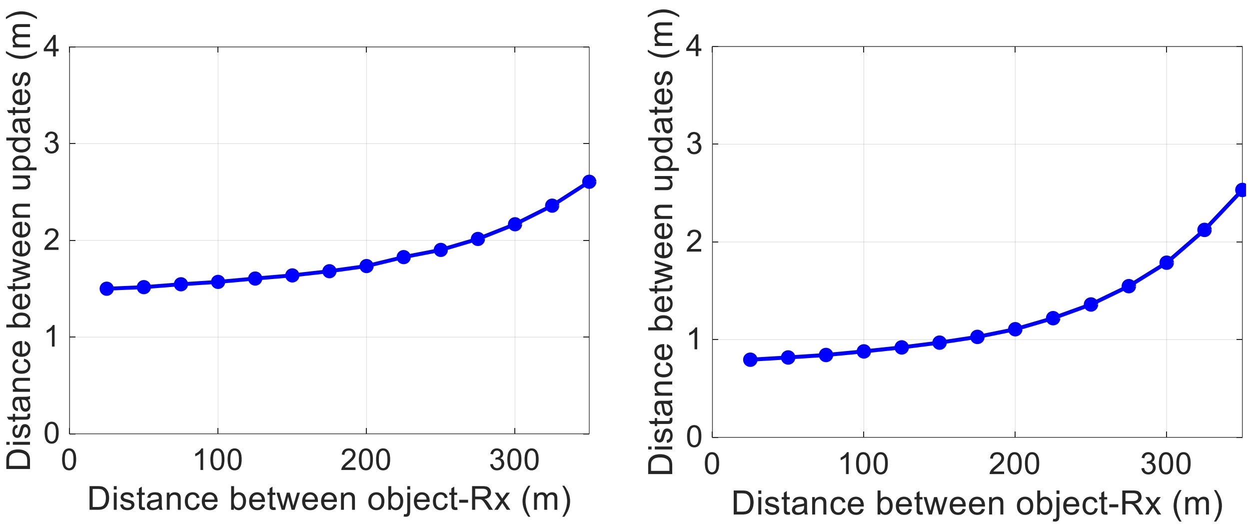
We first highlight the limitations of the current ETSI CPM generation rules to motivate the proposal. In particular, the section evaluates the level of redundancy generated by the current ETSI CPS implementation. To this aim, simulations have been conducted following the scenarios and network configuration defined in Section 2.2.2. ETSI CPM generation rules include information about a vehicle in a CPM every 200ms and 300ms for the low and high traffic density scenarios respectively. We then consider observation time windows of 200ms and 300ms for the low and high traffic density scenarios based on the analysis reported from Figure 44. These values correspond to the time required by ETSI CPM generation rules for a vehicle to send an update about an object in a CPM for the two traffic densities.

Figure 57 plots the number of times a vehicle receives CPMs with data about the same object over the selected observation time windows. These CPMs come from different vehicles that detect the same object. The metric depicted in Figure 57 is referred to as object redundancy. It is represented as a function of the distance between the detected object and the vehicle receiving the CPMs. Figure 57 highlights the redundancy levels resulting from current ETSI CPM generation rules. Rather than receiving a single object update per observation window, on average, vehicles receive more than 5 updates for low and more than 6 updates for high traffic densities respectively up to distances of around 200m. This results that the vehicles receive updates about objects more frequently than really necessary. This is illustrated in Figure 58 that plots the distance travelled by an object between two successive CPMs that include information about that object. Results are again plotted as a function of the distance between the object and the vehicle receiving the CPMs. This figure clearly shows that a vehicle receives updates about a detected object much more frequently than in fact intended by ETSI CPM generation rules. Figure 58 shows that on average a vehicle will receive an object update less than every 1.7m for low density and less than every 1.1m for high density up to distances of around 200m. This is in contrast to the 4m threshold established by the CPM generation rules to decide when an update should be transmitted. Sending frequent updates might be unnecessary from the perception point of view and can significantly increase the load on the communications channel. This can augment packet collisions and reduce the reliability of V2X communications which can ultimately decrease the perception capabilities of CAVs. In the following section, a modification of the current ETSI CPS is proposed to control the unnecessary detected object redundancy while maintaining the objective to minimize changes to the standards.



(a) Low density (b) High density

Figure 57. Object redundancy as a function of the distance between the detected object and the vehicle receiving the CPMs.



(a) Low density (b) High density

Figure 58. Average distance travelled by a detected object between two successive CPMs reporting about this object. Metric represented as a function of the distance between the object and the vehicle receiving the CPMs.

2.3.3.2.2 Proposed Redundancy Mitigation Technique

The objective of the proposal is to reduce the redundancy in the transmission of CPMs without decreasing the perception capabilities of CAVs for short and medium distances since they are critical for the safety of CAVs. The proposal extends the current ETSI CPM generation rules as follows. At every *T_GenCpm*, the proposed algorithm analyses for every detected object the change in the absolute position (ΔP_R) and speed (ΔS_R) since the last time the object was received in a CPM from other vehicles. If $\Delta P\_R \leq P\_Threshold$ and $\Delta S\_R \leq S\_Threshold$, the object is omitted from the current CPM. *P_Threshold* and *S_Threshold* threshold values must be equal or smaller than 4m and 0.5m/s respectively to reduce redundancy. Further, if any one of the given conditions is not satisfied, the algorithm computes the variation of absolute position (ΔP), the variation of speed (ΔS) and the time elapsed (ΔT) since the last time the object was included in a CPM. If at least one of the conditions ΔP>4m or ΔS>0.5m/s or ΔT>1s specified in the ETSI CPM generation rules (Section 2.1.2.1.3) is satisfied, the object is included in the current CPM. The rationale for this proposal is that if a vehicle has recently received an update about an object from other vehicles, there is no need for the vehicle to send another update about this object since neighbour vehicles will have already received the data from other vehicles. This reduces unnecessary redundancy. The pseudo-code of the proposed extension to the ETSI CPM generation rules is described in Algorithm II.

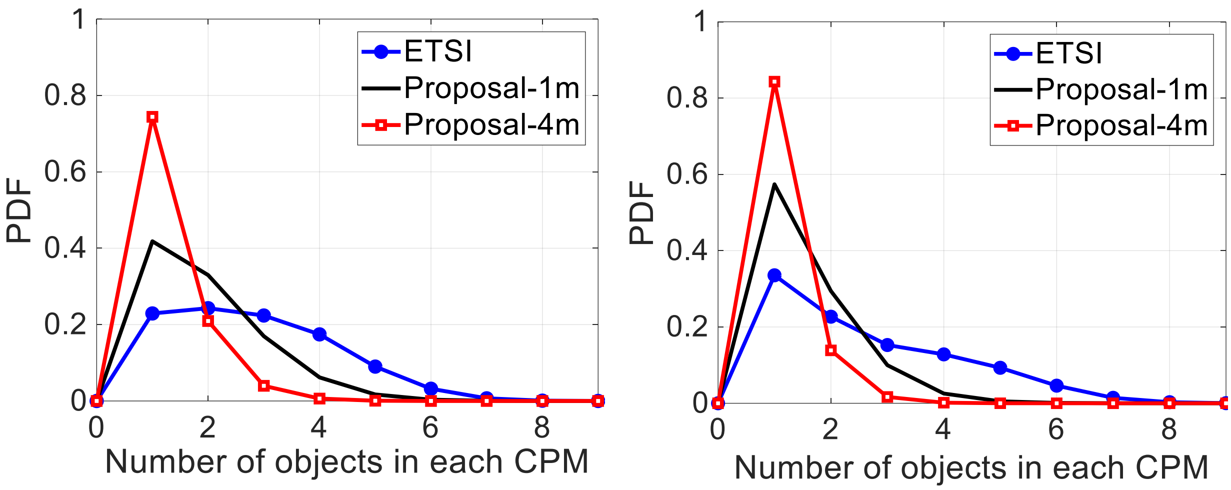
ALGORITHM II.
Input: Detected Objects
Output: Objects (if any) to include in CPM
Execution: Every *T_GenCpm*

```
For every detected object do
   Calculate ΔP_R and ΔS_R since last time received in a CPM
   If ΔP_R < P_Thresholdm && ΔS_R < S_Thresholdm/s then
      Continue
   Else
      Calculate ΔP, ΔS and ΔT since last time included in a CPM
      If ΔP>4m || ΔS>0.5m/s || ΔT>1s then
         Include object in current CPM
      End if
   End If
End For
```

2.3.3.2.3 Evaluation

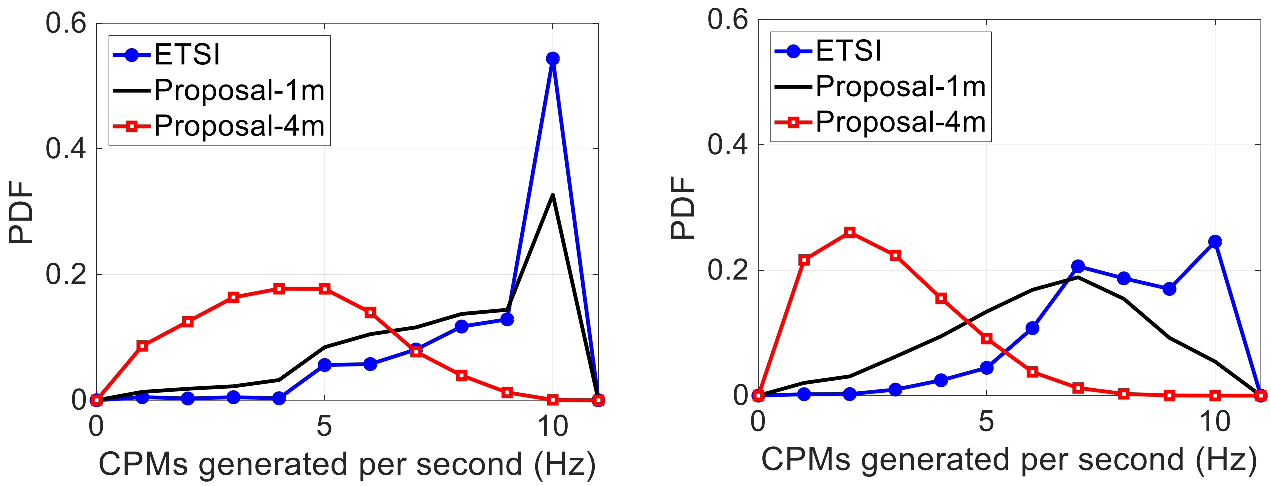
The proposal is analysed using the simulation set-up and conditions described in Section 2.2.2. The proposed algorithm is implemented considering two threshold configurations: (*P_Threshold*=1m, *S_Threshold*=0.5m/s) and (*P_Threshold*=4m, *S_Threshold*=0.5m/s). These configurations are referred to as proposal-1m and proposal-4m in this evaluation.

Figure 59 compares the PDF of the number of objects included in each CPM with the current ETSI generation rules and the proposal. Figure 59 shows that the proposal reduces the number of detected objects included per CPM under low and high traffic densities and for both configurations. The largest reductions are obtained with the proposal-4m configuration. Figure 59 also shows that the proposal reduces the number of objects included per CPM when augmenting the traffic density. This is because when the density increases there are many vehicles that transmit the same redundant data with the ETSI CPM generation rules. The proposal reduces the redundancy and has then a higher impact when the traffic density increases. This is very interesting since higher densities can impinge the networks' scalability. The proposal also reduces the number of CPMs transmitted per second. This is visible in Figure 60 that compares the PDF of the number of CPMs generated per vehicle per second with the ETSI CPM generation rules and the proposal.



(a) Low density (b) High density

Figure 59. PDF of the number of objects included in each CPM.



(a) Low density (b) High density

Figure 60. PDF of the number of CPMs generated per second.

The proposal-4m configuration achieves again the higher reduction levels. These results clearly show that the proposal generates less CPMs per second with smaller size than the current ETSI CPM generation rules. This reduces the channel load as illustrated in Table 13. The channel load is estimated in terms of the average CBR (Channel Busy Ratio). The CBR is defined as the percentage of time that the channel is sensed as busy. Table 13 shows that the proposal significantly reduces the channel load as a consequence of the trends depicted in Figure 59 and Figure 60. In particular, the proposal-1m configuration reduces the CBR by 17%-26% and the proposal-4m configuration by 58%-68% when compared to the current ETSI solution. As expected, Table 13 shows that the CBR increases with the traffic density. However, lower increases are observed with the proposal following the trends observed in Figure 59 and Figure 60. This shows that the proposed algorithm can better cope with increases in the network load. Reducing the CBR and channel load reduces the packet collisions and improves the PDR (Packet Delivery Ratio). This is actually shown in Table 14 that reports the distance up to which a PDR equal or higher than 0.9 is guaranteed[2].

[2] This distance is considered a V2X performance reference by some standardization organizations such as the 3GPP [47].

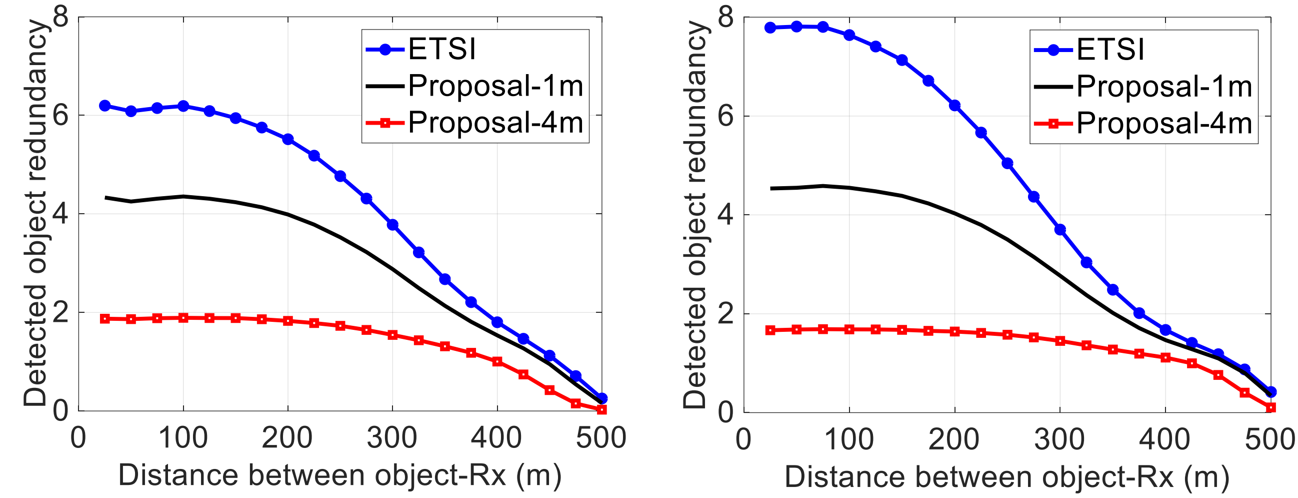
Table 13 . Average CBR (Channel Busy Ratio)

Policy	Traffic density	CBR
ETSI	Low	19.2 %
	High	31.8 %
Proposal-1m	Low	15.9 %
	High	23.4 %
Proposal-4m	Low	8.1 %
	High	10.1 %

Table 14. Distance (meters) with PDR ≥ 0.9

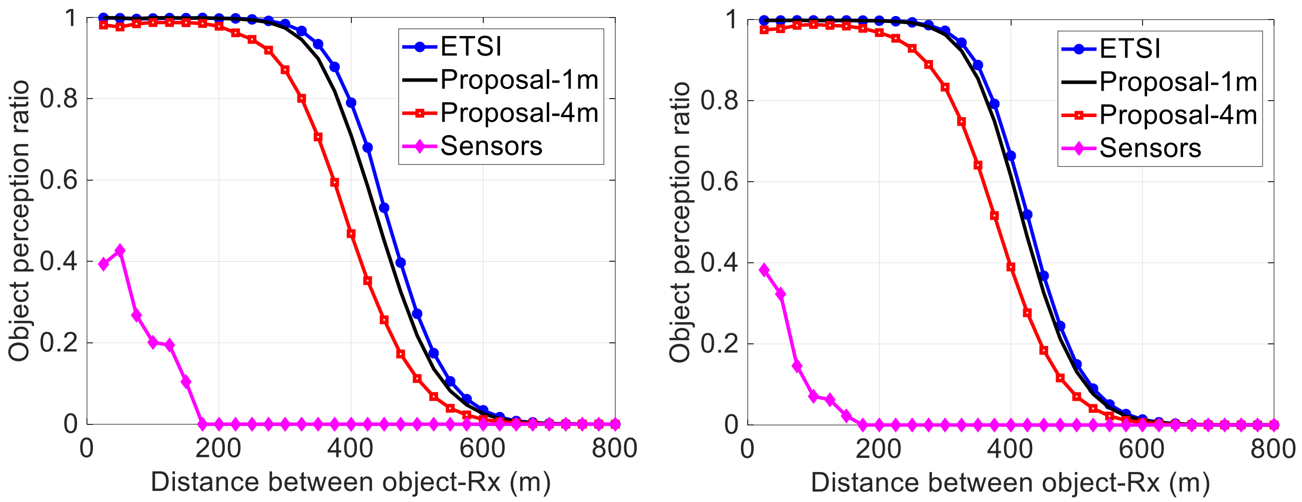
Policy	Traffic density	PDR
ETSI	Low	181m
	High	112m
Proposal-1m	Low	200m
	High	160m
Proposal-4m	Low	250m
	High	233m

Table 14 shows that the proposal increases this distance compared to the current ETSI solution. In particular, the proposal-1m configuration increases it by 10% and 42% in low and high traffic densities, and the proposal-4m configuration by 38% and 108% respectively. These results demonstrate that the proposal increases the reliability of V2X communications. Figure 61 shows the effectiveness of the proposal to reduce the redundancy introduced by current ETSI's CPS solution. The figure depicts the object redundancy as a function of the distance between the object and the vehicle receiving the update or CPM. This metric represents the number of times a vehicle receives CPMs with an update about the same object over the observation time window. The object redundancy decreases with the distance due to the propagation effect that reduces the PDR. Figure 61 shows that the proposal effectively reduces the number of object updates compared to ETSI´s solution in order to control the channel load. This reduction is achieved without sacrificing the perception performance for short and medium distances that are critical for the safety of CAVs. This is illustrated in Figure 62 that compares the perception achieved with the current ETSI CPM generation rules and the proposal. The perception is estimated with the object perception ratio that is defined as the probability to detect an object (i.e. a vehicle in this study) within the observation time window. We consider that a vehicle successfully detects an object if it receives at least one CPM with information about that object during the observation time window. Figure 62 also shows the perception achieved with an autonomous vehicle that only uses its sensors and does not implement V2X communications. In this case, we consider that a vehicle successfully detects an object if the sensors detect the object during the same time window. Figure 62 plots the average object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPMs. Figure 62 shows that relying exclusively on the onboard sensors results in a very low perception performance. The perception is significantly improved when using collective perception or cooperative sensing. Figure 62 shows that the proposal achieves the same (or nearly the same) perception as ETSI´s current solution for the critical short and medium distances (up to around 200m) and both traffic densities. In particular, the perception performance is identical for the proposal-1m configuration. These results show that the proposed algorithm can reduce the redundancy without degrading the perception capabilities compared to current ETSI´s solution at the critical short and medium distances. It should be noted that the performance is evaluated considering only the transmission of CPM messages. Higher channel load levels resulting from the transmission of additional messages (e.g. CAM or MCM messages) could increase the load and degrade the perception achieved with current ETSI's solution. The proposal would be more robust again such increase since Table 13 demonstrates that the proposal significantly reduces the CBR and hence increases the reliability (Table 14). Figure 62 also shows that the performance degrades for higher distances. This is due to the propagation effects that impact more the proposal-4m configuration since it is the one that transmits less CPMs. This configuration is hence more sensitive to packet losses.



(a) Low density (b) High density

Figure 61. Object redundancy as a function of the distance between the detected object and the vehicle receiving the CPM.



(a) Low density (b) High density

Figure 62. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPMs

2.3.3.3 Integration of Look-Ahead and Redundancy Mitigation Algorithms

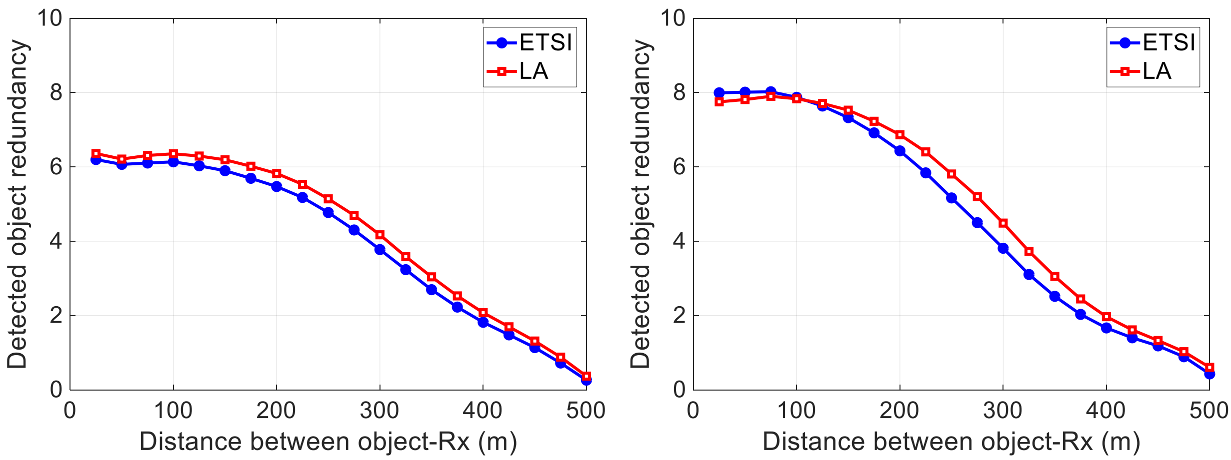
The Look-Ahead (LA) and Redundancy Mitigation (RM) algorithms proposed in Section 2.3.3.1 and Section 2.3.3.2 aim to address the limitations identified in the ETSI message generation rules (see Section2.2.2) and improve the collective perception service. The standalone look-ahead algorithm reduces the number of generated CPMs that has small number of included objects. The standalone redundancy mitigation technique on the other hand reduces the unnecessary redundancy object information shared in the network. Carefully combining these two proposals would utilize the best out of both proposals and improve the overall cooperative sensing. To this aim, different methodology to combine these two algorithms are proposed and an in-depth analysis is performed. The conducted analysis demonstrates that the appropriate combination of the look-ahead and redundancy mitigation algorithms performs better than the standalone algorithm and improves the overall cooperative perception service.

2.3.3.3.1 Motivation

Before defining a combination of LA and RM algorithms, we first analyise in detail the performance metrics discussed in section 2.3.3.1 and section 2.3.3.2 To this aim, simulations have been conducted following the scenarios and network configuration defined in Section2.2.2. ETSI CPM generation rules include information about a vehicle in a CPM every 200ms and 300ms for the low and high traffic density scenarios respectively. Further, the observation time windows of 200ms and 300ms for the low and high traffic density scenarios is selected based on the analysis reported from Figure 44. These values correspond to the time required by ETSI CPM generation rules for a vehicle to send an update about an object in a CPM for the two traffic densities.

First, the object redundancy at the receiver is analysed for the standalone Look-Ahead (LA) algorithm. Figure 63 shows the object redundancy as a function of the distance between the object and the receiving vehicle for the standalone LA and ETSI implementation under the forward sensor configuration. This metric represents the number of times a vehicle receives CPMs with an update about the same object over the observation time window. Figure 63 shows that the LA algorithm slightly increases the redundancy in comparison with the ETSI implementation despite the reduction in CBR (see

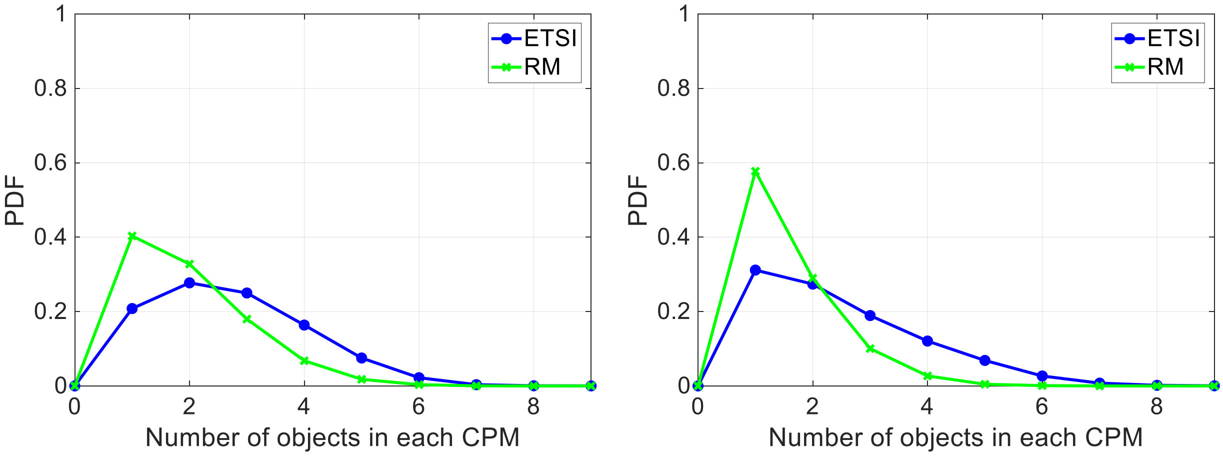
).



(a) Low density (b) High density

Figure 63. Object redundancy as a function of the distance between the detected object and the vehicle receiving the CPM for the forward sensor configuration.

Second, the number of objects included in each CPM are analysed with the RM algorithm. To this aim, the (*P_Threshold*=1m, *S_Threshold*=0.5m/s) is evaluated. Figure 64 compares the PDF of the number of objects included in each CPM with the standalone RM and ETSI implementation. Figure 64 shows that the RM algorithm reduces the number of detected objects included per CPM under low and high traffic densities and for both configurations. This reduces the CBR significantly (see Table 13). However, the RM generates a greater number of CPMs that has small number of objects included. This increases the unnecessary headers in the lower protocol layers that could increase the consumption of channel bandwidth. Figure 63 and Figure 64 show that the standalone Look-Ahead (LA) and Redundancy Mitigation (RM) algorithm have their own inefficiencies. From the analysis performed in Section 2.3.3.1 and Section 2.3.3.2 it is clear that these identified inefficiencies does not significantly affect the cooperative sensing performance. However, reducing these inefficiencies could further improve the overall performance of the cooperative perception. Thus it is necessary to develop different methodologies to combine the Look-Ahead and Redundancy Mitigation techniques to achieve higher performance and efficiency in the cooperative sensing.



(a) Low density (b) High density

Figure 64. PDF of the number of objects included in each CPM.

2.3.3.3.2 Proposals

The objective of combining look-ahead and redundancy mitigation algorithms is to reduce the inefficiencies of the standalone techniques and to improve the overall network performance and perception or sensing capabilities of CAVs. To this aim, two different combination of look-ahead and redundancy mitigation algorithms are proposed and analysed in detail. The algorithms are based on the current ETSI CPM generation rules.

2.3.3.3.3 Look-Ahead & Redundancy Mitigation (LARM) Algorithm

In this Look-Ahead & Redundancy Mitigation (LARM) algorithm, vehicles first check the conditions to generate a new CPM every *T_GenCpm*. The algorithm computes for each detected object the variation of absolute position (ΔP), the variation of speed (ΔS) and the time elapsed (ΔT) since the last time the detected object was included in a CPM. A new CPM is generated if at least one of the conditions specified in Section 2.1.2.1.3 is satisfied following the current ETSI CPM generation rules. If it is the case, the CPM should include the information about the detected objects that satisfy ΔP>4m or ΔS>0.5m/s or ΔT>1s. The pseudo-code for this process is reported in lines 1-8 of Algorithm III. Then, the LARM extends the ETSI CPM generation rules with the LA. The algorithm estimates every time a new CPM must be generated (following the ETSI CPM generation rules) if any of the detected objects that are not included in this new CPM would be included in the next CPM if their current speed and acceleration was maintained. To this aim, the LARM estimates the following parameters:

$$Next\ \Delta P = \Delta P + S \cdot T\_GenCpm \qquad (1)$$

$$Next\ \Delta S = \Delta S + A \cdot T\_GenCpm \qquad (2)$$

$$Next\ \Delta T = \Delta T + T\_GenCpm \qquad (3)$$

where S and A are the current speed and acceleration of the detected object. The look-ahead includes in the current CPM those detected objects that satisfy *Next* ΔP>4m or *Next* ΔS>0.5m/s or *Next* ΔT>1s. Their information (ΔP, ΔS and ΔT) is transmitted in the current CPM instead of the next CPM. The pseudo-code for this process is described in lines 9-16 of Algorithm III.

Finally, the LARM extends the Algorithm III by incorporating RM. For every object that is principally included in the CPM by the previous process, the LARM analyses the change in the absolute position (Δ*P_R*) and speed (Δ*S_R*) since the last time the object was received in a CPM from other vehicles. If Δ*P_R*≤*P_Threshold* m and Δ*S*≤ *S_Threshold* m/s, the object is omitted from the CPM. *P_Threshold* and *S_Threshold* threshold values must be equal or smaller than 4m and 0.5m/s respectively to reduce redundancy. The pseudo-code for this process is described in lines 17-24 of Algorithm III.

ALGORITHM III.
Input: Detected objects
Output: Objects (if any) to include in CPM
Execution: Every *T_GenCpm*

```
1.  Set flag = false
2.  For every detected object do
3.      Calculate ΔP, ΔS and ΔT since the last time included in a CPM
4.      If ΔP>4m || ΔS>0.5m/s || ΔT>1s then
5.          Include object in current CPM
6.          Set flag = true
7.      End If
8.  End For
9.  If flag = true then
10.     For every detected object not included in current CPM do
11.         Calculate Next ΔP, Next ΔS and Next ΔT
12.             If Next ΔP>4m || Next ΔS>0.5m/s || Next ΔT>1s then
13.                 Include object in current CPM
14.             End if
15.     End For
16. End If
17. If flag = true then
18.     For every detected object in current CPM do
19.         Calculate ΔP_R and ΔS_R since the last time received in a CPM
20.             If ΔP_R < P_Redundancy && ΔS_R < S_Redundancy then
21.                 Omit object from current CPM
22.             End If
23.     End For
24. End If
```

2.3.3.3.4 Redundancy Mitigation & Look-Ahead (RMLA) Algorithm

In this Redundancy Mitigation & Look-Ahead (RMLA) algorithm, vehicles first check the conditions to generate a new CPM every *T_GenCpm*. The algorithm computes for each detected object the variation of absolute position (Δ*P*), the variation of speed (Δ*S*) and the time elapsed (Δ*T*) since the last time the detected object was included in a CPM. A new CPM is generated if at least one of the conditions specified in Section 2.1.2.1.3 is satisfied following the current ETSI CPM generation rules. If it is the case, the CPM should include the information about the detected objects that satisfy Δ*P*>4m or Δ*S*>0.5m/s or Δ*T*>1s. The pseudo-code for this process is reported in lines 1-8 of Algorithm IV. Then, the RMLA extends the ETSI CPM generation rules with RM. For every object that is principle included in the CPM by the ETSI CPM generation rules, the RMLA algorithm analyses the change in the absolute position (Δ*P_R*) and speed (Δ*S_R*) since the last time the object was received in a CPM from other vehicles. If Δ*P_R*≤*P_Threshold* m and Δ*S*≤

S_Threshold m/s, the object is omitted from the inclusion of CPM even if it complies with the original ETSI CPM generation rules' conditions. *P_Threshold* and *S_Threshold* threshold values must be equal or smaller than 4m and 0.5m/s respectively to reduce redundancy. The pseudo-code for this process is described in lines 9-19 of Algorithm IV.

Finally, the RMLA extends the Algorithm IV with LA. The RMLA estimates every time a new CPM must be generated (following the ETSI CPM generation rules) if any of the detected objects that are not included in this new CPM would be included in the next CPM if their current speed and acceleration was maintained. To this aim, the RMLA estimates the following parameters:

$$Next\ \Delta P = \Delta P + S \cdot T\_GenCpm \qquad (1)$$

$$Next\ \Delta S = \Delta S + A \cdot T\_GenCpm \qquad (2)$$

$$Next\ \Delta T = \Delta T + T\_GenCpm \qquad (3)$$

where *S* and *A* are the current speed and acceleration of the detected object. The RMLA includes in the current CPM those detected objects that satisfy *Next* ΔP>4m or *Next* ΔS>0.5m/s or *Next* ΔT>1s. Their information (ΔP, ΔS and ΔT) is transmitted in the current CPM instead of the next CPM. It is to be noted that the RMLA could include an object in the CPM that was omitted by the previous processes. The pseudo-code of the process is described in lines 20-27 of Algorithm IV.

ALGORITHM IV.
Input: Detected objects
Output: Objects (if any) to include in CPM
Execution: Every *T_GenCpm*

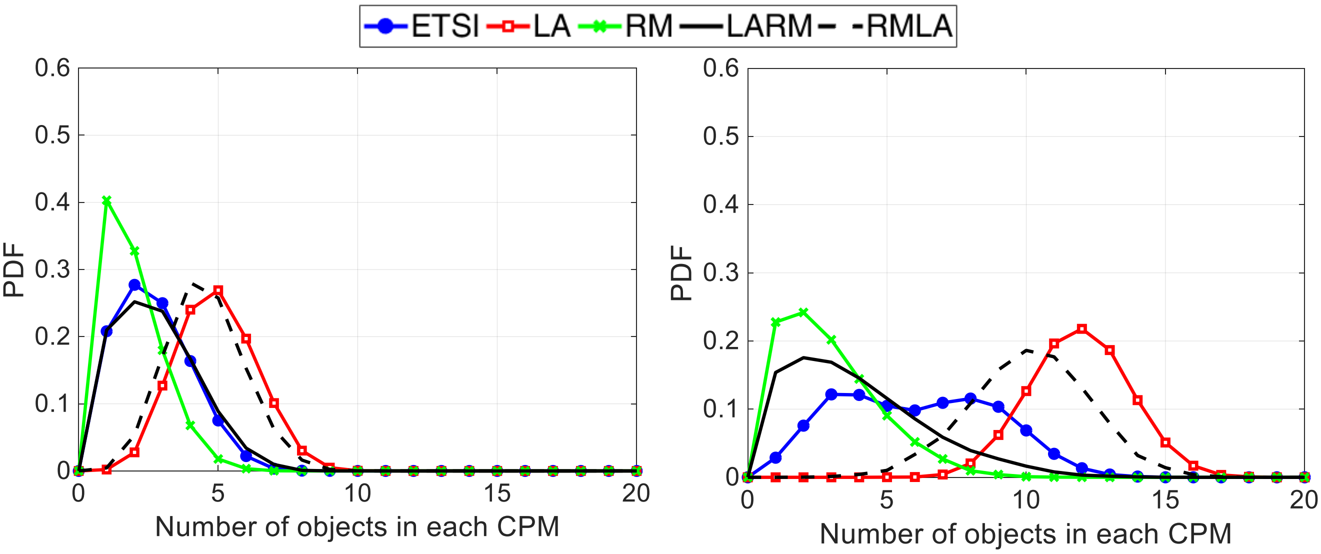
1. Set *flag* = false
2. **For** every detected object **do**
3. Calculate ΔP, ΔS and ΔT since the last time included in a CPM
4. **If** ΔP>4m || ΔS>0.5m/s || ΔT>1s **then**
5. Include object in current CPM
6. Set *flag* = true
7. **End If**
8. **End For**
9. **If** *flag* = true **then**
10. **For** every detected object included in current CPM **do**
11. Calculate ΔP_R and ΔS_R since the last time received in a CPM
12. **If** ΔP_R < P_Redundancy && ΔS_R < S_Redundancy **then**
13. Omit object from current CPM
14. **End if**
15. **End For**
16. **If** no object in the current CPM **then**
17. Set *flag* = false
18. **End if**
19. **End If**
20. **If** *flag* = true **then**
21. **For** every detected object not included in current CPM **do**
22. Calculate *Next* ΔP, *Next* ΔS and *Next* ΔT
23. **If** *Next* ΔP>4m || *Next* ΔS>0.5m/s || *Next* ΔT>1s **then**
24. Include object in current CPM
25. **End If**
26. **End For**

27. **End If**

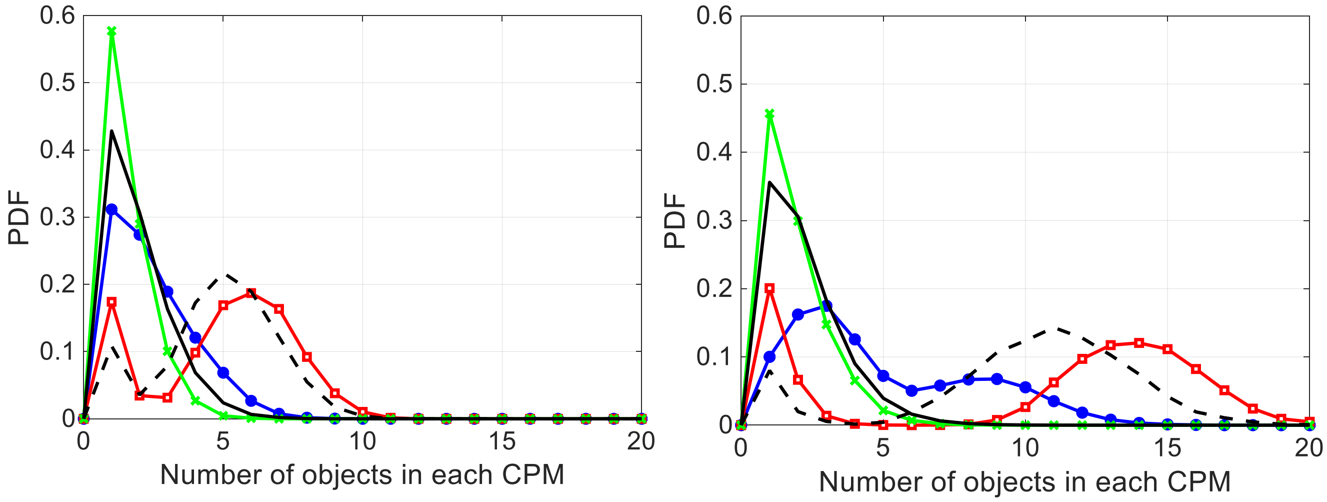
2.3.3.3.5 Evaluation

The proposals are analysed using the simulation set-up and conditions described in Section2.2.2. In addition to the forward sensor configuration, a new 360º sensor configuration is also incorporated in this study. In the 360º sensor configuration, the vehicles are equipped with a single sensor with 150m range and a 360º FoV. The proposed algorithms LARM and RMLA are compared with the standalone Look-Ahead (LA) algorithm, Redundancy Mitigation (RM) algorithm and ETSI implementation. For the analysis, the LARM, RMLA and standalone RM algorithm are implemented considering the threshold: (*P_Threshold*=1m, *S_Threshold*=0.5m/s).

Figure 65 compares the PDF of the number of objects included in each CPM with the current ETSI generation rules and the proposals. Figure 65 shows that the RMLA significantly reduces the effect of generating smaller CPMs as highlighted in Figure 64. In particular, the RMLA proposal increases the number of detected objects included per CPM when compared with the LARM for all traffic densities and sensor configuration. This shows that RMLA anticipates more objects in the current CPM than the LARM and possibly avoids future CPM transmissions. When compared with the standalone LA algorithm, RMLA contains higher number of objects included in each CPM, reducing the message size. Also for higher densities, the RMLA significantly reduces the generation of CPMs that includes a smaller number of objects (see Figure 65.c and Figure 65.d). This is particularly important because, smaller CPMs increase the number of channel access attempts and the number of times the ITS PDU header and the Management and Station Data containers of a vehicle are transmitted which could negatively impact the network performance.



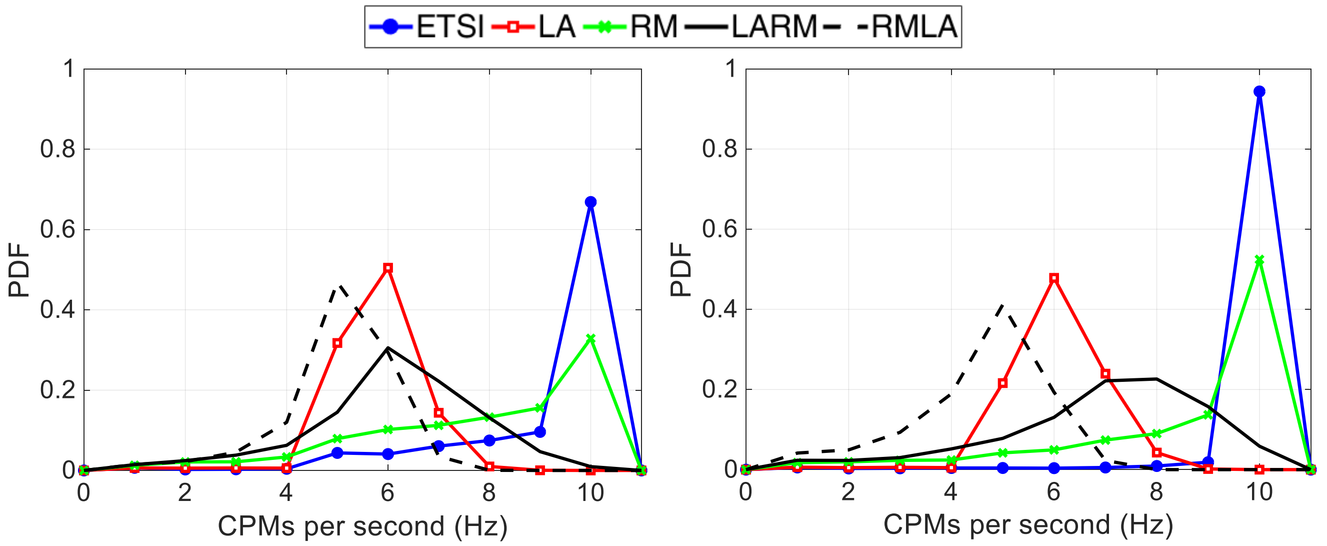
(a) Forward sensors (low density) (b) 360º sensor (low density)



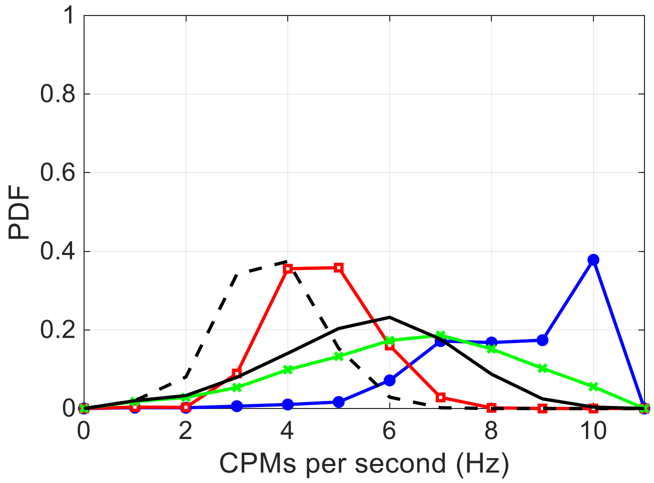
(c) Forward sensors (high density)   (d) 360º sensor (high density)

Figure 65. PDF of the number of objects included in each CPM.

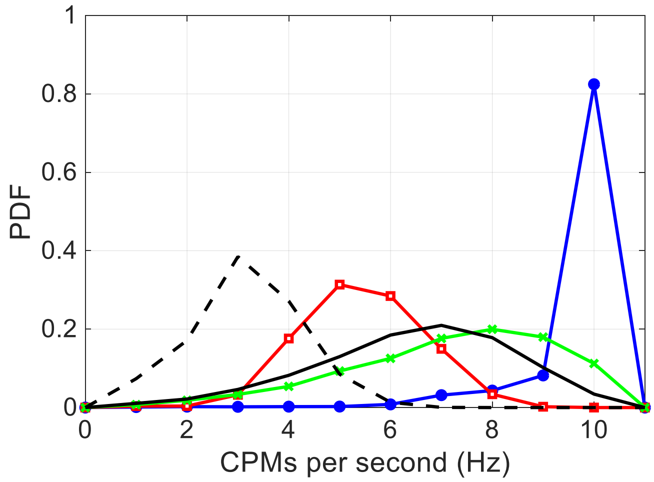
Figure 66 compares the PDF of the number of CPMs generated per vehicle per second with the ETSI implementations and proposals. The results obtained show that the proposed RMLA algorithm significantly reduces the number of CPMs generated per second compared to the current ETSI rules and other proposals. This reduction is achieved for all traffic densities and sensor configurations. This is because whenever a CPM must be generated, the RMLA algorithm anticipates more objects that are going to be included in the next CPM and makes the current CPM larger. This potentially avoids the generation of future CPMs. On the other hand, the LARM algorithm omits all the redundant object information (both included by ETSI generation rules and the look-ahead algorithm) and makes the current CPM smaller. Thus, increasing the chance of generating the next CPM with some of the current omitted objects. From Figure 65 and Figure 66, the LARM significantly reduces the CPM rate and makes each CPM larger by anticipating more objects. This could reduce the channel access in the network.



(a) Forward sensors (low density)   (b) 360º sensor (low density)



(c) Forward sensors (high density)



(d) 360º sensor (high density)

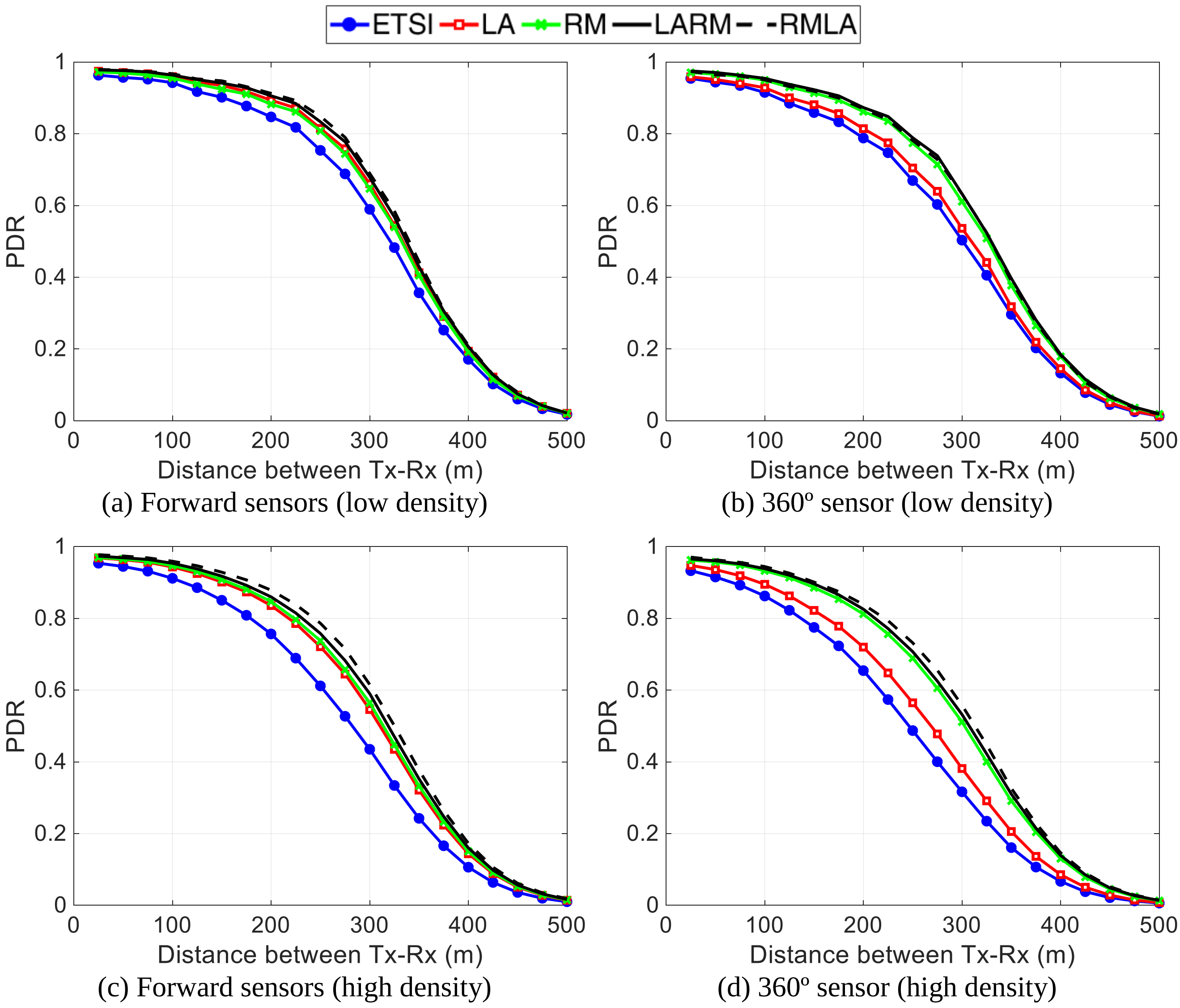
Figure 66. PDF of the number of CPMs generated per second.

Table 15 shows the average channel busy ratio experienced for the proposals and the ETSI implementation under different sensor configurations and traffic densities. The CBR is measured by each vehicle every second. The CBR is a measure of the channel load, and it is defined as the percentage of time that the channel is sensed as busy. A high CBR value indicates that the channel is very loaded and hence risks saturating. If this happens, the communications performance degrades and the packet delivery ratio decreases [49]. Table 15 shows that the ETSI implementation has higher CBR when compared with proposals. On the other hand, the proposals reduce the CBR significantly and higher reductions are observed for the LARM and RMLA. For low density, both LARM and RMLA reports similar CBR due to the fact that the LARM increases the CPM generation rate while the RMLA increases the objects included in each CPM, thus consuming the channel bandwidth in a similar fashion. With the increase in traffic density, more transmitters generate CPMs which increases the redundancy in the network and RMLA efficiently manages the CPM generation rate and the objects included in each CPM reducing the CBR by 10%-12% when compared with the LARM. When compared with the ETSI implementation, RMLA reduces the CBR significantly by 42%-77% for the higher densities.

Table 15. Average CBR (Channel Busy Ratio)

	Low density		**High density**	
	Forward sensors	**360º sensor**	**Forward sensors**	**360º sensor**
ETSI	19.8%	27.6%	33.7%	45.3%
LA	15.7%	24.9%	24.5%	38.3%
RM	16.0%	19.0%	24.0%	27.9%
LARM	13.9%	17.1%	22.0%	26.1%
RMLA	13.4%	17.5%	19.3%	23.4%

The channel load or CBR has an impact on the PDR (Packet Delivery Ratio). The PDR is defined as the probability of successfully receiving CPM as a function of the distance between the originating and receiving vehicles. Figure 67 plots the PDR for the proposals and ETSI implementation under different sensor configurations and traffic densities. The degradation of the PDR with the distance is due to the radio propagation effects. The lower PDR observed for the ETSI implementation for all sensor configurations and traffic densities is due to high packet collisions or interference. Figure 67 shows that the combined proposals LARM and RMLA achieve higher PDR for all configurations when compared with the standalone proposals. In particular, the RMLA achieves higher PDR when compared with the LARM for higher density. This shows that the RMLA adapts better with higher traffic density. From Table 15 and Figure 67 we can observe that the combined RMLA achieves better network performances.



(a) Forward sensors (low density)

(b) 360º sensor (low density)

(c) Forward sensors (high density)

(d) 360º sensor (high density)

Figure 67. Packet Delivery Ratio as a function of the distance between transmitter and receiver.

Figure 68 compares the perception achieved with the current ETSI implementation and the proposals. The perception is estimated with the object perception ratio that is defined as the probability to detect an object (i.e. a vehicle in this study) within the observation time window. We consider that a vehicle successfully detects an object if it receives at least one CPM with information about that object during the observation time window. Figure 68 plots the average object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPMs. Figure 68 shows that the ETSI implementation and proposals achieve higher perception ratio (above 95%) for the critical short and medium distances (up to around 250m) under different sensor configurations and traffic densities. When analysing the perception achieved at higher distances (e.g. above 250m), Figure 68.a and Figure 68.b show that the RMLA proposal achieves the same (or nearly the same) perception as ETSI´s implementation for the low traffic densities under two sensor configurations. The zoom subplots shown in Figure 68.a and Figure 68.b highlight that the RMLA proposal achieves the same perception as ETSI´s implementation for higher distances. However, Table 15 shows that the RMLA algorithm reduces the CBR effectively by 32%-36% when compared with the ETSI implementation for the low density. It is to be noted that for low densities (see Figure 68.a and Figure 68.b), the standalone LA achieves higher perception at higher distances when compared with the RMLA proposal. However, the increase in the perception is smaller while the LA proposal increase the CBR by 15%-30% when compared with RMLA proposal. Figure 68.c and Figure 68.d show that both RMLA and standalone LA proposal achieve higher perception when compared with the ETSI implementation and other proposals for the high traffic densities under two sensor configurations. The zoom subplots shown in Figure 68.c and Figure 68.d highlight that the RMLA proposal achieves the same perception as standalone LA proposal. However, Table 15 shows that the LARM effectively reduce the CBR by 21%-39% when compared with the standalone LA for high traffic densities.

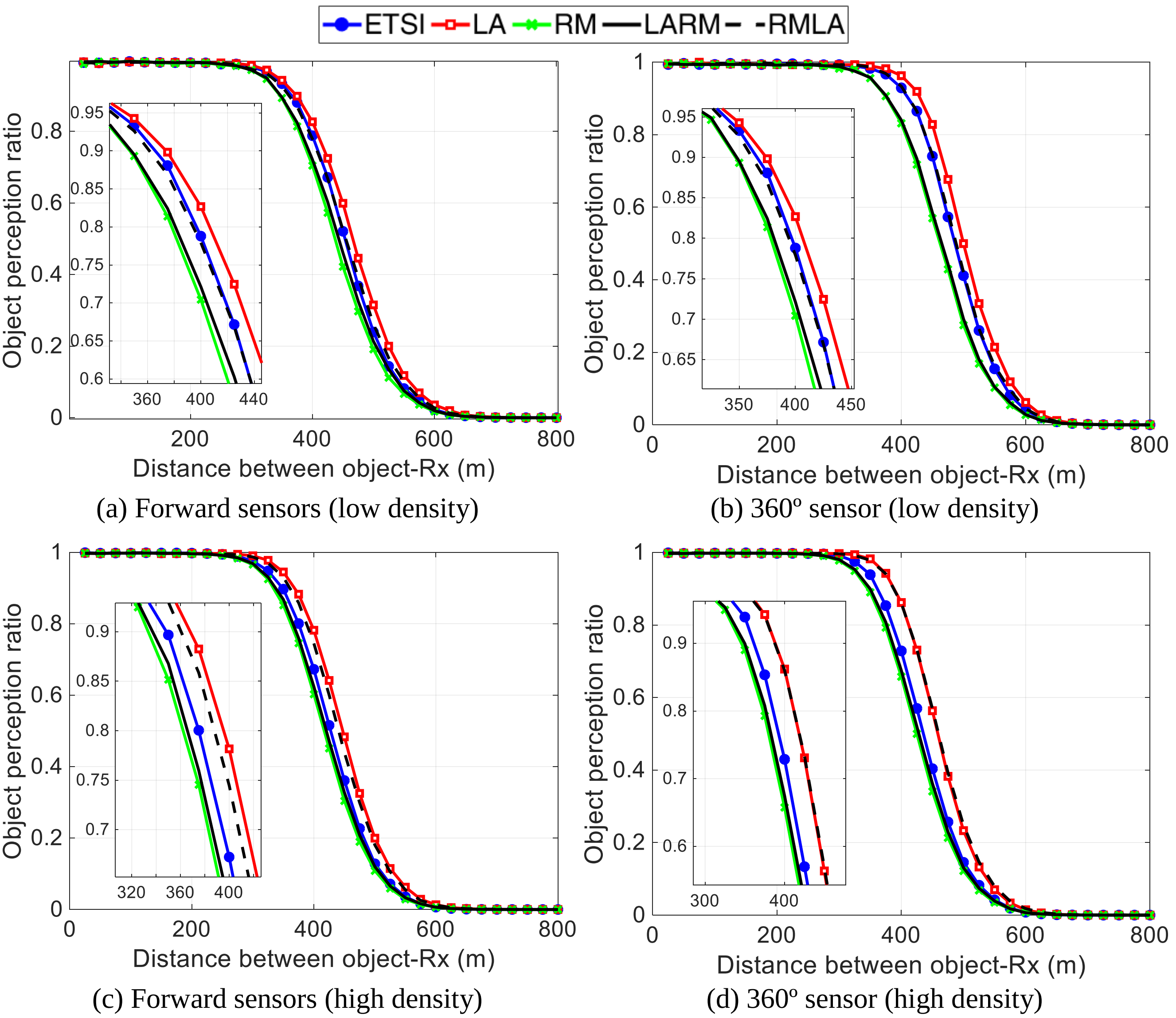
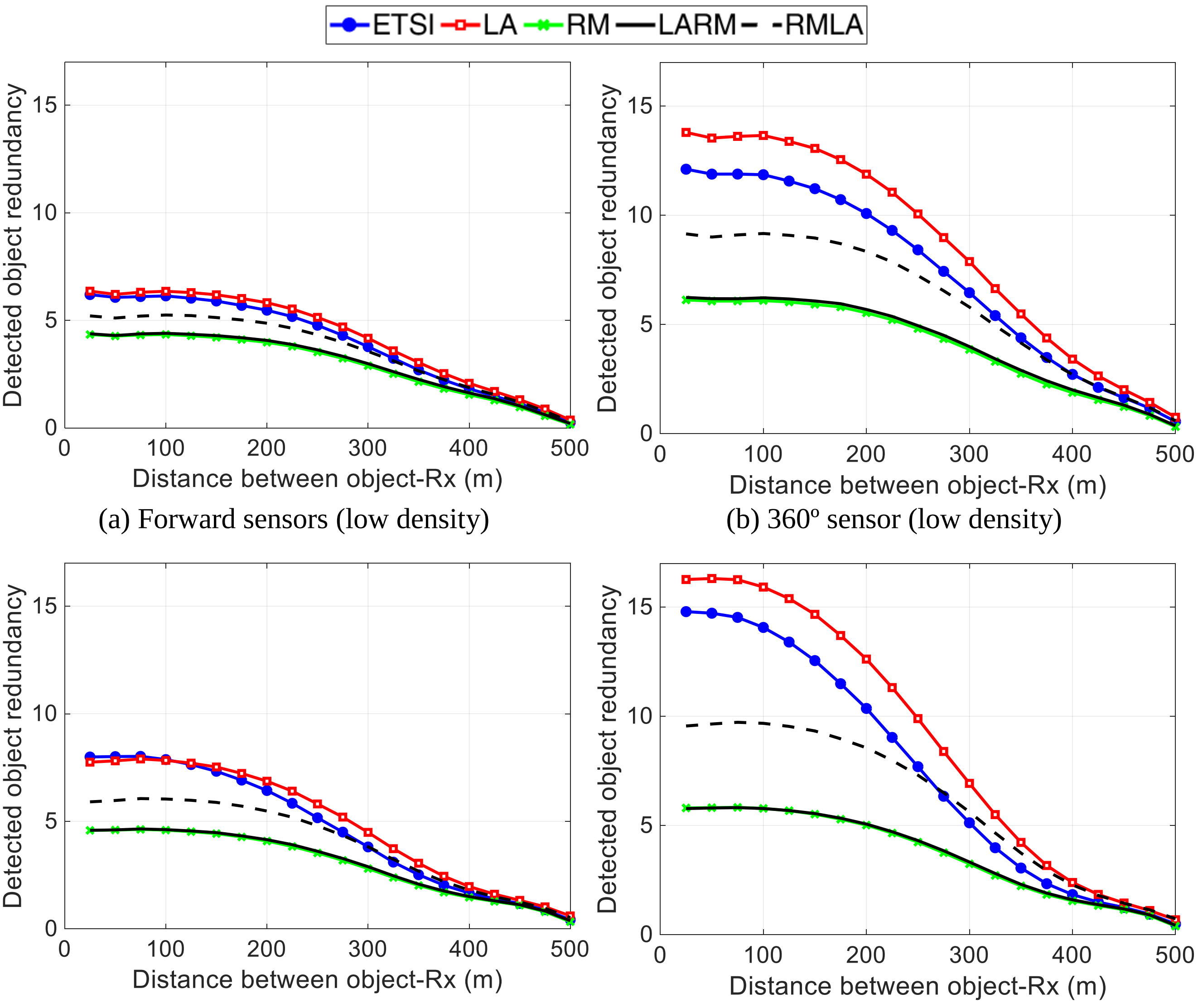


Figure 68. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPMs.

Figure 69 shows the effectiveness of the RMLA proposal to reduce the redundancy introduced by the standalone LA proposal. The figure depicts the object redundancy as a function of the distance between the object and the vehicle receiving the update or CPM. This metric represents the number of times a vehicle receives CPMs with an update about the same object over the observation time window. The object redundancy decreases with the distance due to the propagation effect that reduces the PDR. Figure 69 shows that the RMLA proposal effectively reduces the number of object updates compared to the ETSI´s implementation and standalone LA proposal in order to control the channel load. This reduction is achieved without sacrificing the perception performance that are critical for the safety of CAVs. Figure 69 also shows that the standalone RM and LARM achieves the lower redundancy while reducing the perception at higher distances (see Figure 68). This clearly shows that the combination RMLA performs better than the LARM in terms of network (see Table 15 and Figure 67) and application performances (see Figure 68 and Figure 69).



(a) Forward sensors (low density)

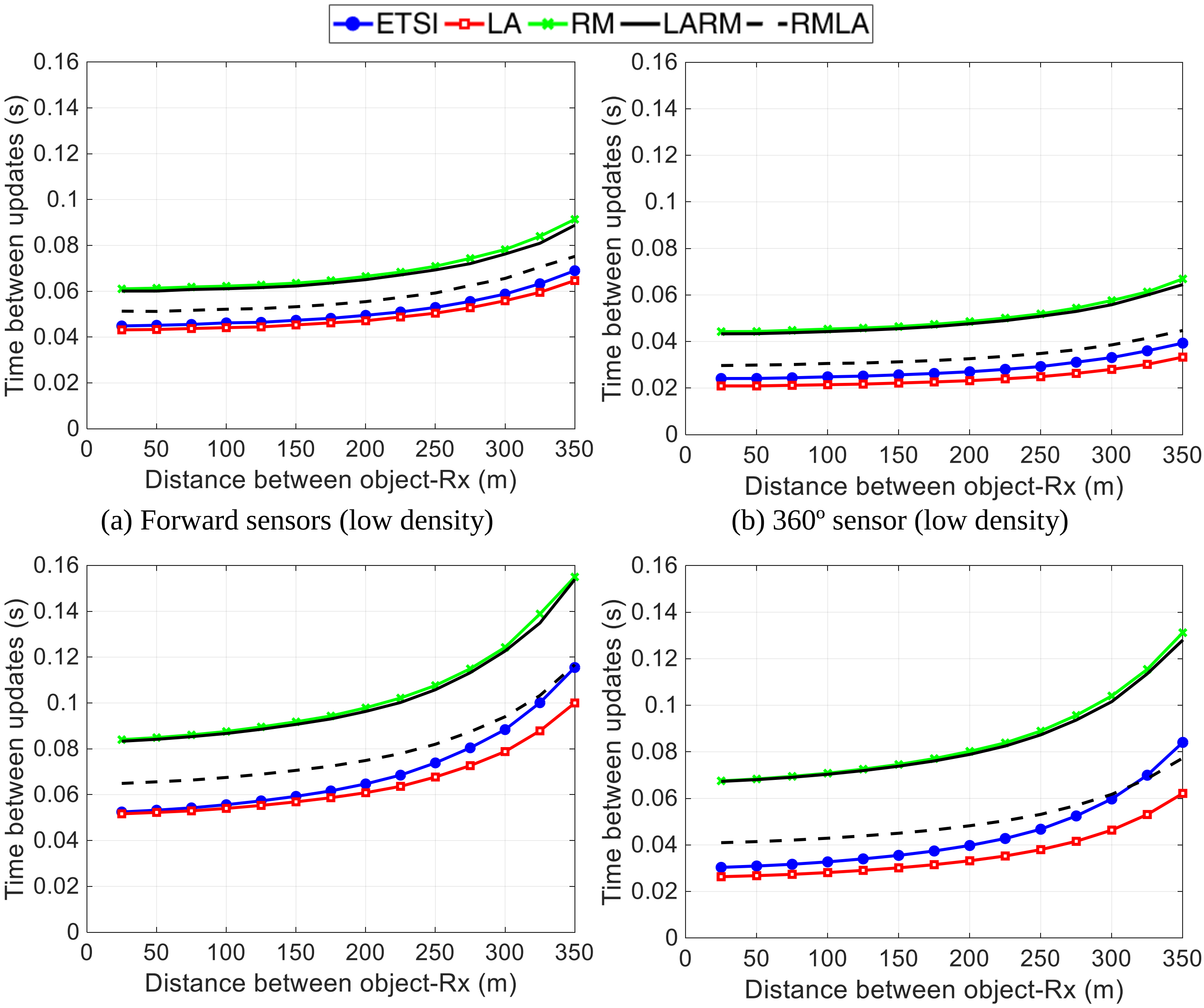
(b) 360º sensor (low density)

(c) Forward sensors (high density)

(d) 360º sensor (high density)

Figure 69. Object redundancy as a function of the distance between the detected object and the vehicle receiving the CPM.

The perception achieved with the RMLA proposal is also analysed in terms of how often a vehicle receives updates about a detected object. The updates can be received from any neighbouring vehicle that has detected the same object. Figure 70 plots the average time between object updates as a function of the average distance between the object and the vehicle receiving the CPMs. In Figure 70, it is shown that the standalone RM and LARM proposals report higher time between updates due to the removal of higher number of objects from the current CPM. This makes the current CPM smaller and increases the generation rate. On the other hand, the standalone LA proposal and ETSI implementation reports lower time between updates while increasing the redundancy (see Figure 69) and CBR (see Table 15**)**. The RMLA proposal reports time between updates closer to the standalone LA proposal and ETSI implementation while reducing the CBR significantly (see Table 15) and achieving higher perception (see Figure 68). This clearly shows that RMLA omits the unnecessary redundant object in CPM and proving frequent object updates close to the standalone LA proposal and ETSI implementation.



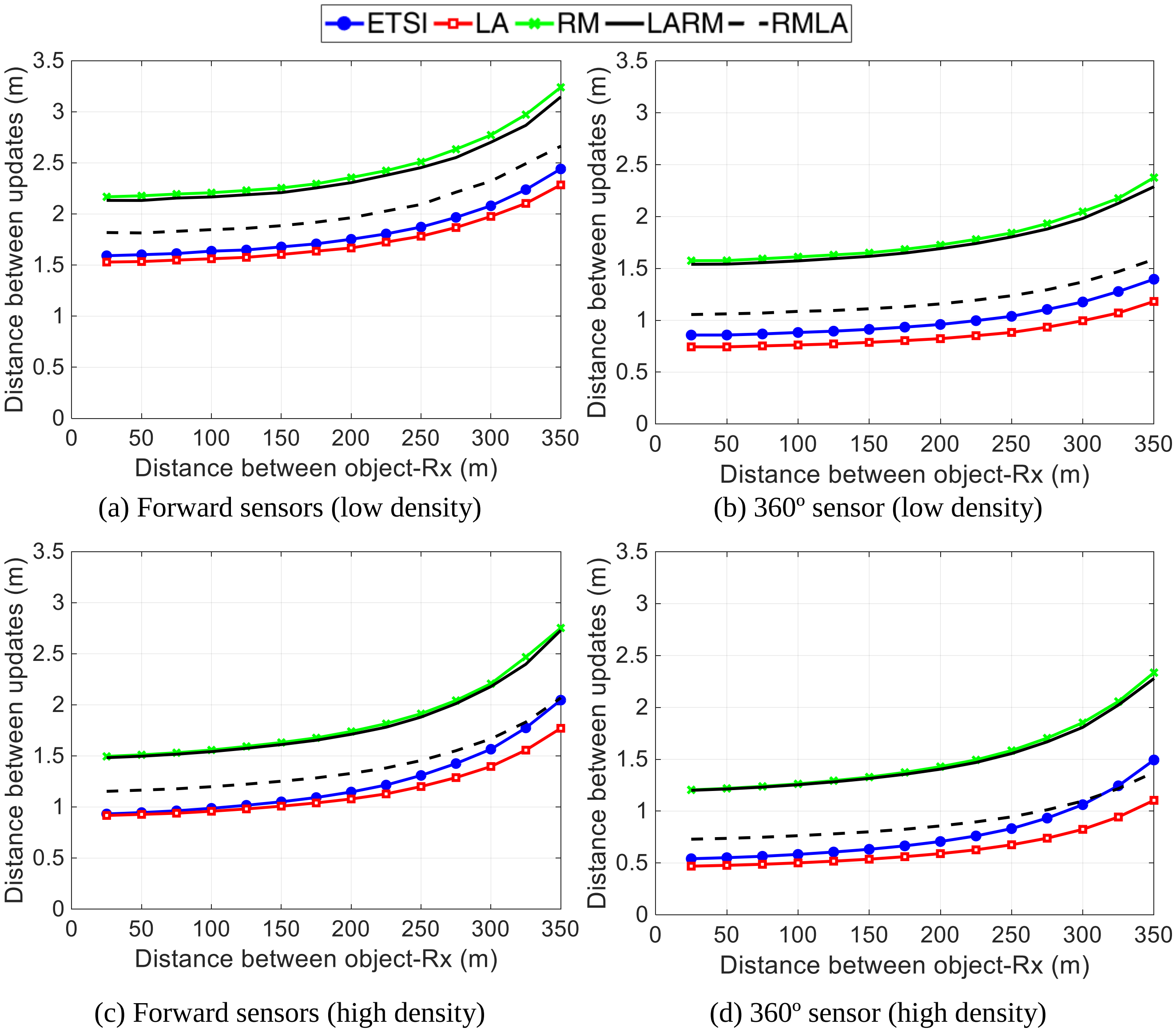
(a) Forward sensors (low density) (b) 360º sensor (low density)

(c) Forward sensors (high density) (d) 360º sensor (high density)

Figure 70. Average time between object updates as a function of the distance between the detected object and the vehicle receiving the CPM.

To further investigate the timeliness of the received information, Figure 71 plots the distance travelled by objects between two successive received CPMs with information about the same object or vehicle. In this case, the metric is named distance travelled between updates and is represented as a function of the distance between the object and the vehicle receiving the CPMs. It is important to emphasize that the CPMs including information about the same object or vehicle might be transmitted by different (multiple) vehicles. Similar trends are observed in Figure 71 and Figure 70.

From these results, the combination of the standalone LA and RM algorithms achieves better performance. The analysis also showed that the RMLA performs better than the LARM and improves overall performance of the cooperative sensing.



(a) Forward sensors (low density)

(b) 360º sensor (low density)

(c) Forward sensors (high density)

(d) 360º sensor (high density)

Figure 71. Average distance travel of an object between updates as a function of the distance between the detected object and the vehicle receiving the CPM.

3 Cooperative Driving

The introduction of autonomous vehicles is expected to improve traffic safety, reduce the fuel consumption of vehicles and improve the efficiency of traffic. As stated in Section 2.1.1.1, AVs will be equipped with different types of on-board sensors (e.g. cameras, LIDARs or RADARs) to perceive their environment. However, these sensors do not facilitate the dynamic interaction of vehicles, and AVs can only sense the environment and (try to) infer what other AVs are doing. V2X communications can facilitate the exchange of information about the driving intentions so that vehicles can coordinate their manoeuvres. Manoeuvre coordination allows vehicles to avoid errors in the estimation of other vehicles intentions, adapt their current trajectory based on the dynamics of neighbour vehicles and facilitates the coordination of the manoeuvres among vehicles. In the TransAID project, the road infrastructure supports the coordination of manoeuvres using V2I communications. Such support does not imply that the infrastructure will manage the manoeuvres of vehicles. Instead, TransAID defined multiple services (see Deliverable 2.2 [50]) in which the infrastructure provides advice, notifications or information that vehicles can utilize to coordinate their manoeuvres.

3.1 State of the art

AVs are being designed to handle autonomously diverse traffic conditions and scenarios. However, automated driving might not always be possible (e.g. due to an unforeseen situation that the vehicle does not know how to handle) and a transition of control will be required [51]. Complex traffic situations with an elevated number of ToCs can negatively impact the traffic safety and efficiency [52]. Cooperative manoeuvring can help reducing ToCs and hence mitigating their negative effects. A cooperative manoeuvre is defined as the coordination of the manoeuvres of two or more vehicles for a safer and more efficient driving.

The cooperative manoeuvres defined so far are generally designed to solve specific traffic situations. For example, the AutoNET2030 project developed a cooperative lane change solution that is based on the reservation of (relative) space on the road [53]. Figure 72 shows the message flow of the cooperative lane change defined by the AutoNET2030 project. The vehicle that wants to perform a lane change (i.e. originating station) broadcasts a *Lane Change Request* message to find a vehicle willing to cooperate (i.e. target vehicle). Vehicles receiving this message will answer with a unicast *Lane Change Response* message informing whether they are able to cooperate or not. The originating station selects the most appropriate target vehicle and informs all vehicles in the lane change area about the selected target vehicle using a *Lane Change Announce* broadcast message that is periodically transmitted. Then, the target vehicle opens the required headway and both vehicles start the preparation for the cooperative lane change. Once the target vehicle is prepared, it sends a *Lane Change Prepared Notification* message to inform the originating vehicle that the lane change can be initiated. Then, the originating vehicle executes the cooperative lane change. Following the AutoNET2030 solution, Kesting et al. define in [54] a cooperative lane change manoeuvre that takes into account the neighbour vehicles. In particular, the cooperative lane change parameters (e.g. headway, longitudinal acceleration, etc.) are defined with the aim to minimize the induced overall braking of all involved vehicles.

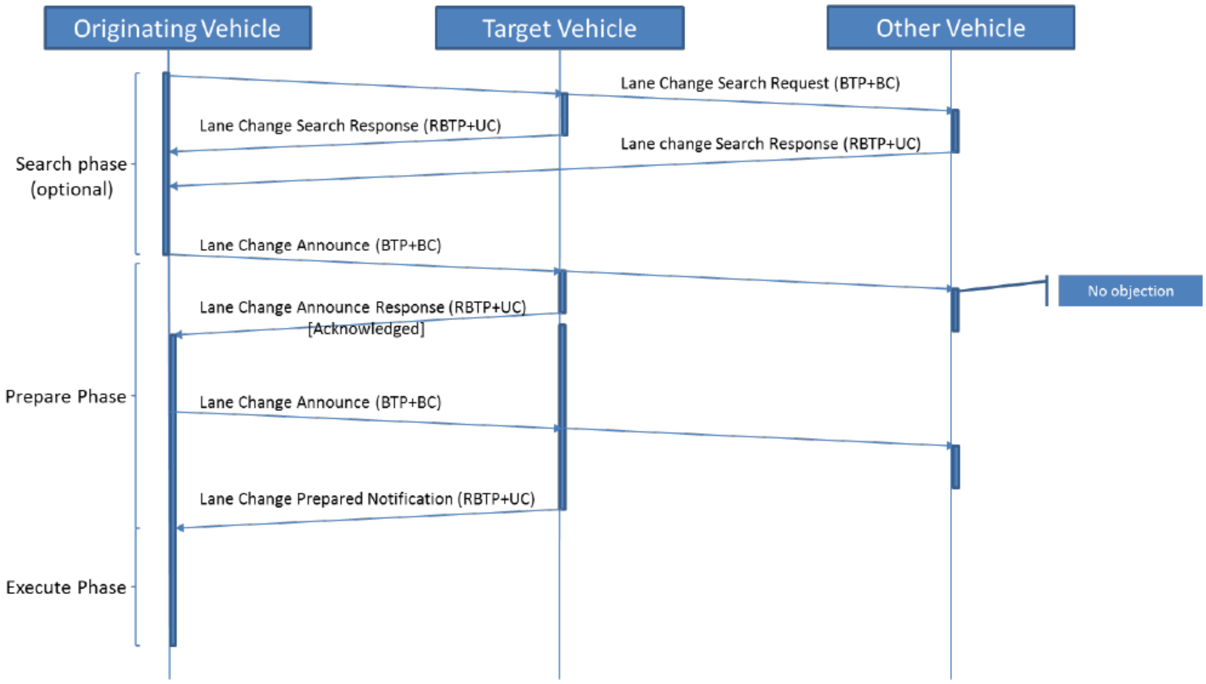


Figure 72. Message flow of the AutoNET2030 cooperative lane change [55].

The i-GAME project designed a cooperative manoeuvre solution for coordinating the merge of two platoons [56]. The proposed solution is based on a sequential basis where: 1) vehicles select a pair in the other platoon; 2) the selected pair creates a gap for the merge; and 3) the selected pair informs the originating vehicle that the lane change can be executed. Furthermore, the i-GAME project also designed a cooperative intersection passing manoeuvre based on the creation of virtual platoons of vehicles [56]. Vehicles approaching the intersection and willing to cooperate form a virtual platoon to establish the order in which the vehicles will enter in the intersection and the adequate gaps in order to ensure that all vehicles drive through the intersection in a safe way.

The approaches studied in UnCoVerCPS [57] are more generic and holistic towards systems development with formal guarantees and vehicle automation is one example application. One of the studied use cases is collaborative lane-change negotiation between two autonomous vehicles, and the review includes vehicle dynamics and control, collision avoidance, trajectory planning, and also V2V communication aspects.

The objective of the D3CoS project [58] was to develop methods, techniques and tools for system engineers and to embed them in industrial system development processes to support affordable development of highly innovative cooperative human-machine systems. Automotive-centred aspects were focused on cooperation between several vehicles (traffic perspective) and within one vehicle (on-board perspective) while the car acts as an agent controlled by a combination of human and artificial driver being in a social environment. With that, effects on traffic flow were investigated.

The previous solutions target specific traffic manoeuvres and might not be directly applicable to other manoeuvres. In contrast, Lehmann *et al*. [59] proposed a cooperative manoeuvre solution that is designed with the aim to be applied to every type of manoeuvre and scenario. The solution is based on the exchange of the planned and desired trajectories of the cooperative vehicles. Based on these trajectories, vehicles can identify if there are potential conflicts with the trajectories of other vehicles and coordinate with them in order to define a cooperative manoeuvre.

3.1.1 ETSI approach on manoeuvre coordination

The ETSI Technical Committee on ITS has recently started a work item ('DTS/ITS-00184') on Maneuver Coordination Service that is in charge of defining concepts and messages which can be used to coordinate manoeuvres between vehicles [60]. The goal is to create a common framework for the implementation of cooperative manoeuvres. At the time of writing this document the standardization process is on its early stages. An agreement has not been settled on how the manoeuvres of vehicles shall be coordinated. Currently there is one proposal based on the work of Lehmann *et al.* [59]. The proposal is based on the use of V2V communications for the exchange of the planned and desired trajectories of vehicles. Based on this exchange of planned and desired trajectories, vehicles detect the need to coordinate their manoeuvres. Then, the involved vehicles define the type of coordination and finally, the cooperative manoeuvre is executed.

Following this proposal, all vehicles periodically transmit a manoeuvre coordination message including their planned trajectories. This allows identifying the need to coordinate manoeuvres when the computed desired trajectory intersects with the received planned trajectories of neighbouring vehicles. In addition, transmitting the vehicles’ planned trajectories avoids others to do this estimation which can be subject to errors. Figure 73 shows an example of cooperative manoeuvre where vehicles exchange the planned and desired trajectories. In this example, the grey CAV wants to overpass a slow truck. In this context, the grey vehicle will need to compute its desired trajectory and detect whether this trajectory will generate any traffic conflict with either the desired or planned trajectories of surrounding vehicles. To do so, the grey CAV compares its desired trajectory with the trajectories received from surrounding CAVs. For each received trajectory, the grey vehicle computes if there is any potential conflict and if so, it computes which has the right of way. If the grey vehicle does not have the right of way, the desired manoeuvre cannot be executed without the coordination of the involved vehicles. This is exactly the case of the top subfigure of Figure 73 where the green vehicle has the right of way and intersects with the desired trajectory of the grey vehicle. When the grey vehicle detects this conflict, it also broadcasts within the MCM its desired trajectory. The green CAV receives the MCM from the grey CAV and considers the desired trajectory as a request for coordination since it also detects that the grey’s CAV desired trajectory intersects with its planned trajectory. If the green vehicle is willing to cooperate, it will send a new MCM with an updated planned trajectory that is computed to allow the grey vehicle’s desired trajectory (i.e. the overpass of the slow truck). When the grey CAV receives the green CAV’s new planned trajectory, it realizes the green CAV is willing to allow its desired trajectory. Then, the green CAV’s desired trajectory will become its planned trajectory and it will start the overtaking manoeuvre as its shown in the bottom subfigure of Figure 73. It is important to note that all other neighbouring vehicles are also aware of the cooperative manoeuvre taking place since all CAVs are periodically transmitting MCMs. An important aspect of this proposal that is being taken into account under ETSI is that the coordination of manoeuvres is governed by right of way rules. That means that if the vehicles that possess the right of way are not willing to cooperate, the manoeuvres will not take place and the desired trajectories will not be executed.

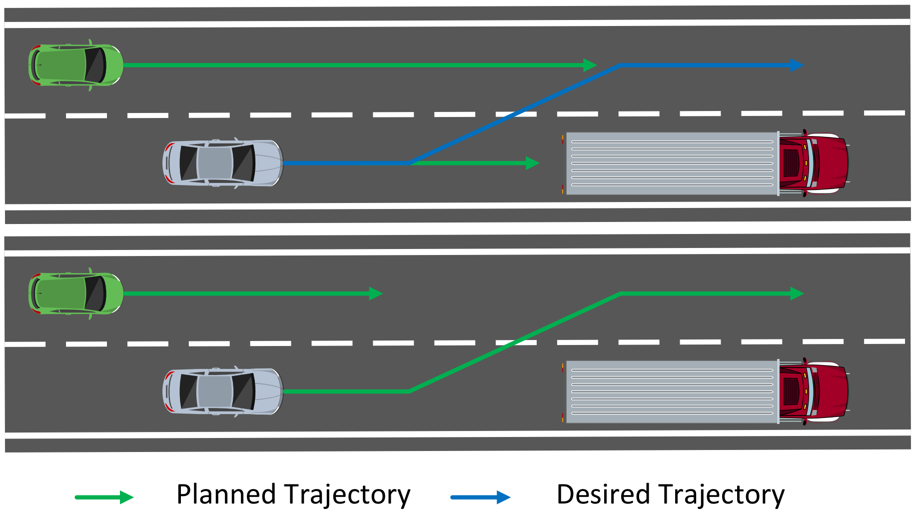


Figure 73. Example of cooperative manoeuvre.

3.1.2 TransAID proposal

As part of the work that is being conducted in TransAID to contribute to the ETSI's MCS (see Annex A), the TransAID project extends the current manoeuvre coordination approach under discussion at ETSI giving to the road infrastructure the opportunity to support manoeuvre coordination under certain scenarios and conditions. To do so, TransAID is defining a message structure for the MCM that varies with the type of originating station. Hence, the vehicles transmitting MCMs will employ the *VehicleManeuverContainer* container while the RSUs transmitting MCMs will employ the *RSUSuggestedManeuverContainer* container as specified in the D 5.1 [4]. Some of the benefits of using the infrastructure to support the manoeuvre coordination include:

Neutral coordination: currently, the road infrastructure is utilized to support the traffic management under particular traffic conditions such as traffic jams, peak hours or under the presence of roadworks. This approach, which seeks supporting the management of multiple manoeuvres of different vehicles in a small area, can be a challenge task for a fully distributed solution. Following this approach in the context of TransAID, the infrastructure can provide support, in the form of advice, to CAVs in the coordination of their manoeuvres so that vehicles can take better decisions. Service 1 defined by the TransAID project can serve as an example of this situation. In a scenario where roadworks block a part of the road, the infrastructure can provide suggestions about alternative paths to follow in order to overpass the roadworks and coordinate the manoeuvres of vehicles. This support from the infrastructure is expected to facilitate the merging of vehicles from different lanes and so to reduce the traffic disruptions. Hence, the support from the infrastructure could be considered as a natural evolution of current road traffic signalling systems.

Enhanced perception: any manoeuvre coordination approach is triggered when vehicles detect the need for coordination. In a fully distributed approach, the detection is in principle limited by the range of the V2V communications. On the other hand, RSUs can be strategically located at specific areas characterized by complex traffic situations that might require frequent manoeuvre coordination. In addition, the manoeuvre coordination supported by the infrastructure can benefit from the extended V2I range due to a higher elevation of the antennas and better propagation conditions. RSUs can obtain information about the traffic streams through the received CAM and CPM messages. Furthermore, the data of these messages can be combined with the data obtained from road sensors installed in the area (e.g. inductive loops or cameras) to further improve the perception capabilities and increase the detection range. These benefits would allow that the infrastructure detects earlier the need for manoeuvre coordination, and hence it will increase the available time and space for the execution of the manoeuvre coordination in the vehicles. Additionally, the enhanced perception of the infrastructure, thanks to the fusion of different sources of information, allows the definition of cooperative manoeuvres that can be designed to improve the overall traffic in terms of safety and efficiency. This is particularly useful under mixed traffic scenarios where conventional, connected and automated vehicles coexist.

Coordination of multiple vehicles: Complex traffic situations could require the coordination of multiple vehicles. Coordinating multiple vehicles through the V2V distributed approach that is currently being considered at ETSI requires a pairwise and sequential coordination of the manoeuvres. That is, in order to coordinate the manoeuvre of three vehicles, two of them will define a cooperative manoeuvre and then the third one will coordinate with one of the other two. This increases the time needed to coordinate the manoeuvres of all vehicles and hence it has a potential negative impact in the road traffic. On the other hand, following the TransAID proposal, RSUs can act as a common (and neutral) coordination entity that provide advices, notifications or information that vehicles can utilize to coordinate their manoeuvres.

3.2 First Iteration

3.2.1 Message flow for the TransAID services

The TransAID project is defining a set of traffic management procedures and protocols to enable the smooth coexistence of automated, connected, and conventional/legacy vehicles, especially at Transition Areas. To this aim, TransAID follows a hierarchical approach that includes the implementation of control actions at different layers including centralised traffic management, infrastructure, and vehicles. In addition, TransAID has identified, so far, five different services and has proposed different solutions to address their Transition Areas (see Deliverable 2.2). The traffic management procedures employed for each Service rely on the communication between vehicles, and between vehicles and the infrastructure. The different messages employed by the TransAID services are defined in Deliverable 5.1. This section defines the V2X message flow between vehicles, and between vehicles and the infrastructure, that are needed to implement the traffic management procedures defined in the Deliverable 4.2 [5].

3.2.1.1 Message flow common to all TransAID services

All the TransAID services have in common the transmission of the cooperative awareness and collective perception messages that provide information about the vehicles and detected objects on the road. In particular, the CAM provides status information (e.g. location, speed, acceleration, heading, etc.) about the ego-vehicle while the CPM provides information about other vehicles/obstacles detected by the ego-vehicle. Both messages must be regularly/periodically transmitted following the message generation rules defined by ETSI. The generation rules for the CAM are defined at the ETSI standard EN 302 637-2 [14]. The generation rules for the CPM are currently under standardization [34]. The current standardization status of the CPM is described in Section 2.1.2.

The traffic management centre combines the information received in the CPM and CAM messages with other information extracted from road sensors. The fused information is used to create a virtual map of the traffic which is employed to define the traffic management procedures of the TransAID services.

3.2.1.2 Service 1: Prevent ToC/MRM by providing vehicle path information

The scenario of application of Service 1 is a three-lane road blocked by a roadworks zone as defined in the Deliverable D2.2 [50]. In order to overpass the roadworks zone, vehicles are temporarily allowed to use the bus lane (see Figure 74). This action may not be properly handled by CAVs, and therefore it could produce some ToCs or MRMs in the scenario. In order to keep traffic flowing smoothly, the TMC can assist these CAVs in planning their path around the roadworks zone. This is done by providing the CAVs with proper path information which allows them to use the bus lane at the adequate road section.

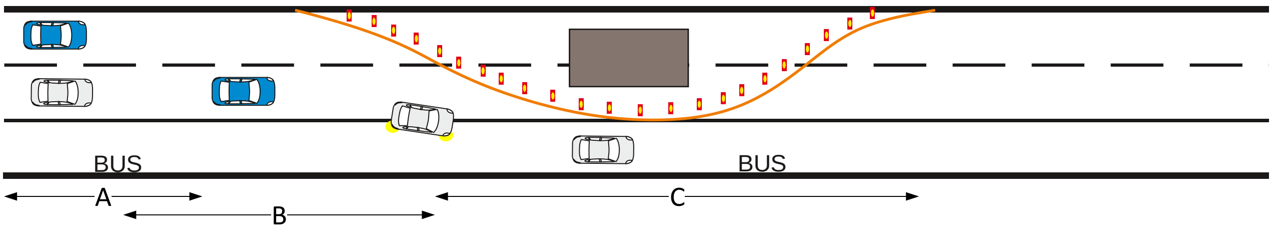


Figure 74. Scenario layout of Service 1 (A is the information transmission zone, B the merge zone and C the road works zone).

The traffic management logic of Service 1 is defined in the Deliverable 4.2. The TMC (regularly/periodically) broadcasts path information to the vehicles entering the information transmission zone (zone marked as ‘A’ in Figure 74). The path information refers to the bus lane that the CAVs can use. Upon the reception of this information CAVs will update their trajectory in order to move to the bus lane in the merge zone (zone marked as ‘B’ in Figure 74) to overpass the roadworks zone (zone marked as ‘C’ Figure 74). If necessary, the TMC will instruct CAVs in the merge zone that are already on the bus lane to increase the headway in order to facilitate the merging of other vehicles. CAVs will be advised to use the default headway again when they enter the roadworks zone.

The execution of Service 1 requires the exchange of messages between vehicles, and between vehicles and the infrastructure. Figure 75 describes the message flow or sequence of messages that need to be exchanged between vehicles, and between vehicles and the infrastructure, in order to execute Service 1 in the scenario defined in Figure 74.

First of all, the TMC (through the RSU) broadcasts the roadworks alert and the permission to temporarily use the bus lane to overpass the roadworks zone to all C(A)Vs in the information transmission zone (see Figure 75). To this aim, the TMC employs two different messages following the V2X message set defined in Deliverable 5.1. The DENM (Decentralised Environmental Notification Message) is employed to alert vehicles that the roadworks are blocking the road. Specifically, the *RoadWorksContainerExtended* container is employed, which gives information about the lanes closed by the roadworks (i.e., location/area that the roadworks zone occupies). The MAPEM is employed to inform C(A)Vs that the bus lane can be temporarily used by all types of vehicles in order to overpass the roadworks. Upon the reception of these messages, CAVs will compute again their future trajectories (planned and desired) taking into account the information included in the MAPEM and DENM messages. If the CAVs detect that they have to modify the current trajectory, they will send an MCM message to inform nearby CAVs and RSUs about the new planned trajectory.

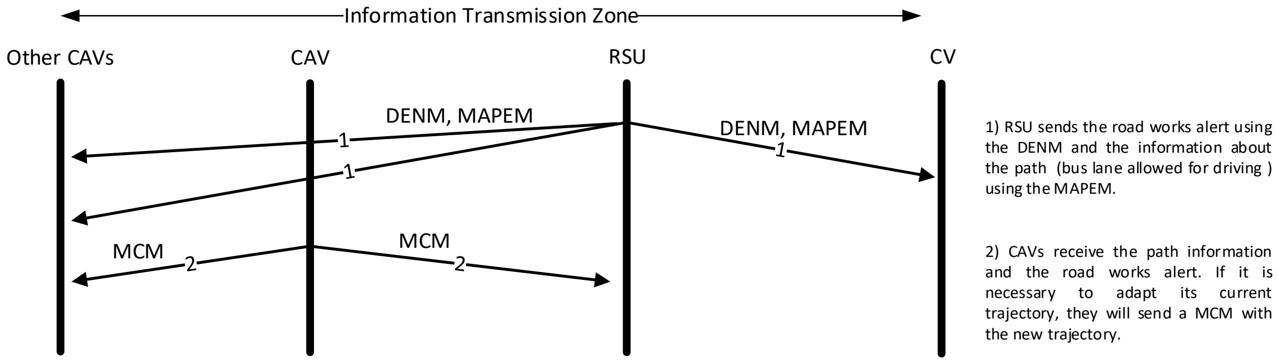


Figure 75. Message flow in the Information Transmission Zone.

In parallel to the transmission of the DENM and MAPEM messages shown above, the TMC monitors the vehicles that are in the merge zone (see Figure 75). If the TMC detects that there are vehicles in the left lanes that need to find a gap for merging to the bus lane, it will advise the CAVs in the bus lane to increase their headway. Thus, the gap between vehicles that are in the bus lane will increase and this will facilitate the merging of vehicles that are in the left lanes. The transmission of this advice will be done employing the *car following advice* object defined in the *RSUSuggestedManeuverContainer* container of the MCM message (see D5.1 [4] for details). Upon reception of the MCM, the CAVs that are located in the bus lane are expected to update their planned trajectories (i.e. increase their headway). This will trigger the transmission of an MCM message that includes the updated trajectory and the confirmation to the TMC that this CAV is willing to follow the advice. As a result, CAVs in the left lane(s) would be aware of the additional gaps that the CAVs in the right lane are creating. In addition, CAVs in the left lane(s) would update their planned trajectories accordingly. The change of the planned trajectory implies that these CAVs would also transmit an MCM with the new trajectory to inform the surrounding CAVs and RSUs.

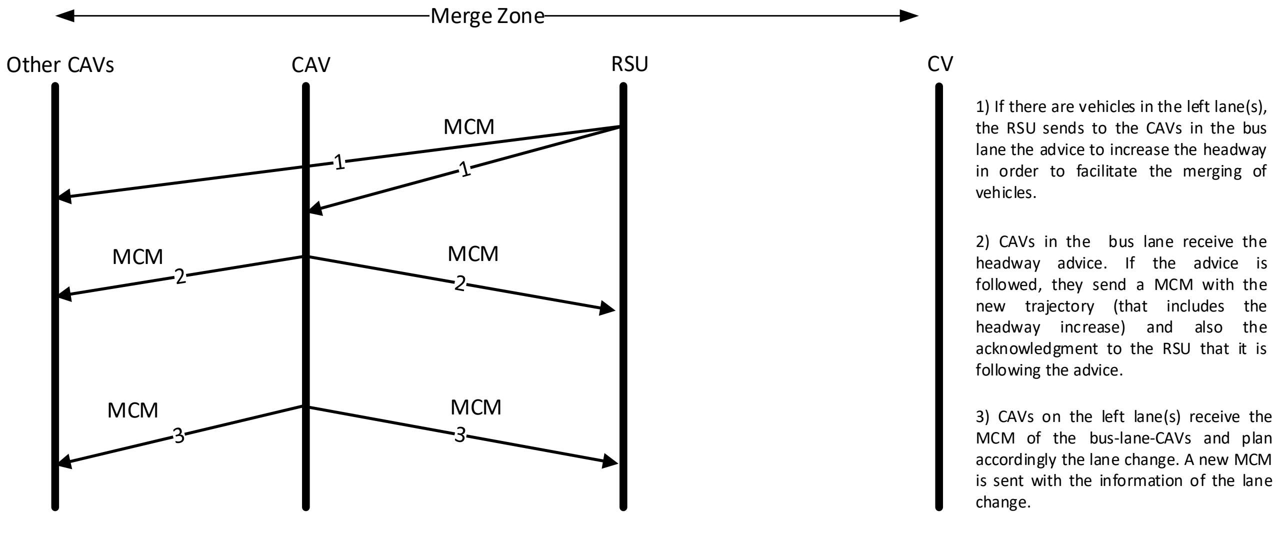


Figure 76. Message flow in the Merge Zone.

Finally, Figure 76 shows the exchange of messages between the TMC (through RSU) and CAVs that is used to set the headway to the default value. This message exchange happens when CAVs are entering the roadworks zone. At this point in time, the TMC sends an advice to the CAVs asking them to reset their headway to the default value (the default value depends on the type of vehicle). Again, this is done using the *car following advice* object of the *RSUSuggestedManeuverContainer* container of the MCM. The CAVs that receive this advice compute whether they have to modify their current trajectory in order to follow the headway advice. If this is the case, they would send a new MCM message indicating their new trajectory.

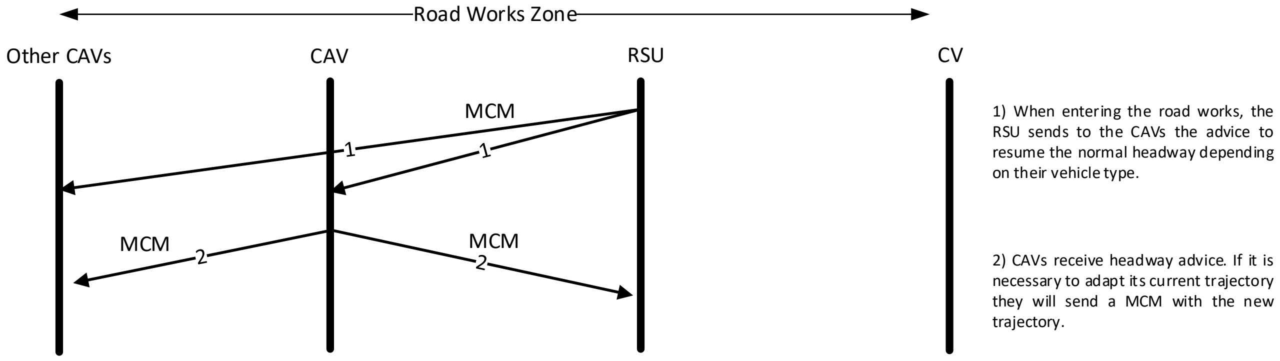


Figure 77. Message flow in the Road Works Zone.

3.2.1.3 Service 2: Prevent ToC/MRM by providing speed, headway and/or lane advice

The scenario of application of Service 2 is a two-lane road with an on-ramp lane on the right as defined in Deliverable D2.2. The RSU monitors the area and provides guidance to CAVs on the on-ramp lane to facilitate the merging process (see Figure 78). This is done by identifying the available gaps in the main road and providing the adequate speed advice to on-ramp CAVs in order to safely merge to the main road.

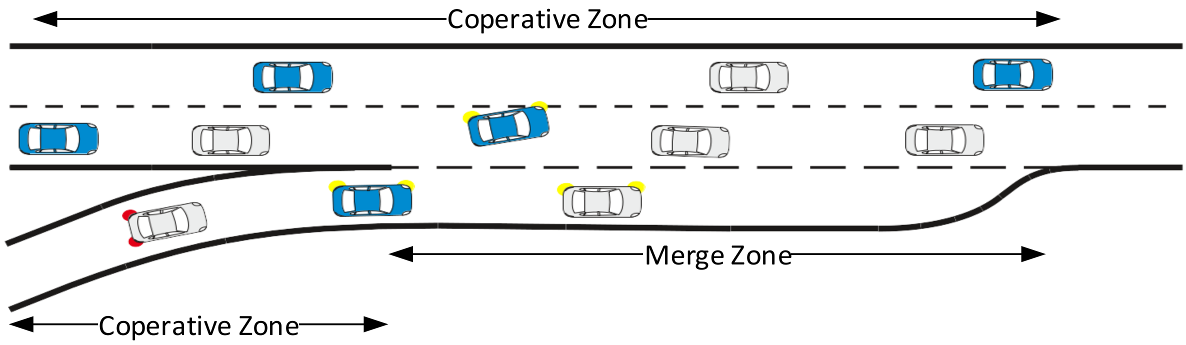


Figure 78. Scenario layout of Service 2.

The traffic management logic of Service 2 is defined in the Deliverable 4.2 [5]. The RSU monitors both, the vehicles coming from the (two-lane) main road, and the vehicles coming from the on-ramp road, that are approaching the merge zone. Then, the RSU computes the gaps available in between the vehicles located in the main road and evaluates whether these gaps are enough for the CAVs coming from the on-ramp lane to perform the merge. If the RSU identifies some gaps in the main road, it sends individual speed advice to the on-ramp CAVs in order to offer guidance in the merging process. For those cases in which the RSU cannot identify a gap large enough to perform the merge, the RSU will advise those CAVs to do an early ToC and request the human driver to take over the merging process.

The following message flow describes the sequence of messages that need to be exchanged between the vehicles, and between the vehicles and the infrastructure, in order to execute Service 2 in the scenario defined in Figure 78.

As shown in Section 3.2.1.1, the RSU continuously monitors the whole area and gathers information about the vehicles (i.e. speed, position, ego-lane leader gap) using the received CAM and CPM messages. When a C(A)V enters the cooperative zone, through the inner lane of the main road, the RSU requests it to keep the current lane until the end of the Merge Zone. This is already a common measure at merging areas with a solid line on the left and a dashed line on the right of the lane separation. It creates space on the outer lane for merging and makes the model more predictable. The RSU performs this request to the C(A)Vs using the *lane change advice* and the *car following advice* objects defined in the *RSUSuggestedManeuverContainer* container of the MCM (see Figure 79). Upon the reception of this message, the C(A)Vs send back an acknowledgement to the RSU using their next MCM. It is important to note that C(A)Vs do not have to modify their trajectories as the advice is to maintain their current lane. This simplifies the task of the RSU of computing the available gaps in the main road. Once these gaps are calculated, the RSU sends individual speed advice to the on-ramp CAVs to facilitate the merging. Again, this is done employing the *car following advice* object defined in the *RSUSuggestedManeuverContainer* container of the MCM. Upon the reception of this advice, the on-ramp CAVs modify accordingly their trajectories. This will trigger the transmission of an MCM message that includes the new trajectory and the confirmation that the CAV is willing to follow the speed advice sent by the RSU.

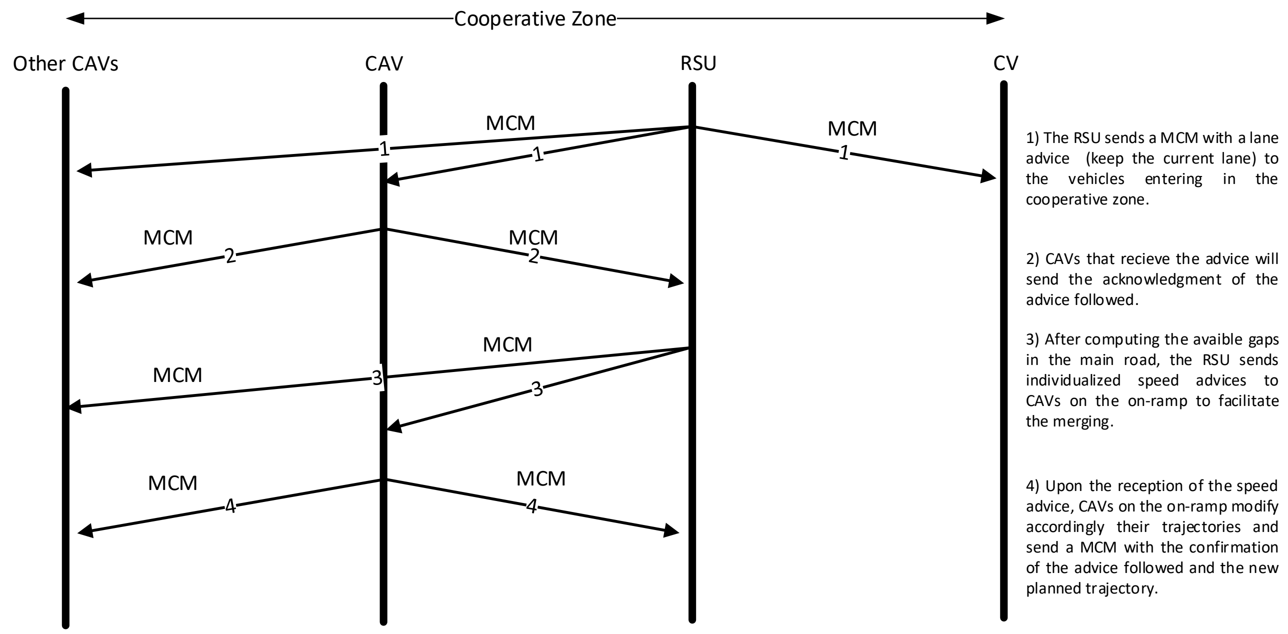


Figure 79. Message flow in the Cooperative Zone.

In order to guarantee that a safe merge process is performed, the RSU keeps monitoring the trajectories of the vehicles in the merge zone. In case no gaps are found in the main road, or the speed advice sent by the RSU is no longer valid, e.g. because the intended gap was closed unexpectedly, the RSU requests the CAVs to perform a ToC (see Figure 80). Note that the ToC advice will be sent as soon as the RSU detects that the merging will not be possible (CAVs can receive the ToC advice r in the cooperative zone or in the merge zone). After the ToC, the driver of the vehicle is in charge of the merging process. The ToC advice is sent using the *ToC advice* object defined in the *RSUSuggestedManeuverContainer* container of the MCM.

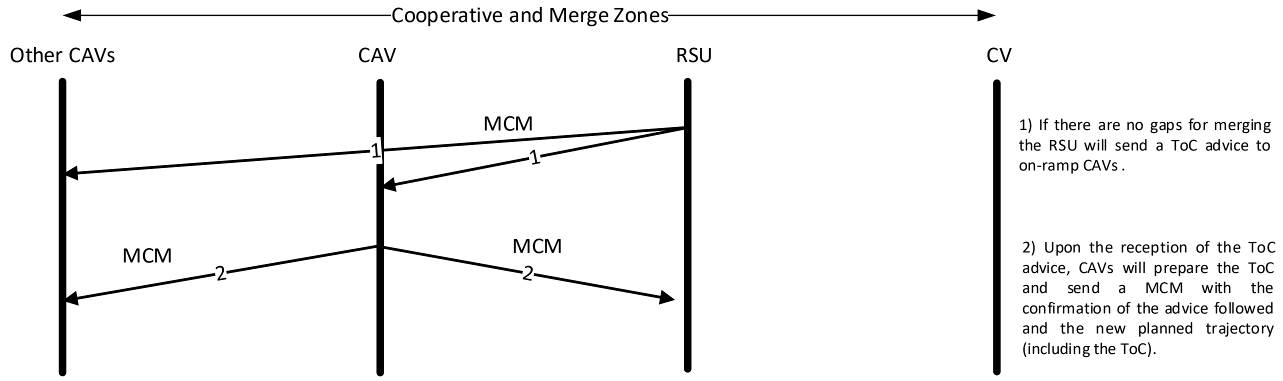


Figure 80. Message flow in the Cooperative and Merge Zones

3.2.1.4 Service 3: Prevent ToC/MRM by traffic separation

The interaction between automated and non-automated vehicles, especially at highway merge areas (see Figure 81), can create dangerous situations due to the unpredictable behaviour of human drivers. This can result in that CAVs need to perform a ToC or MRM. However, CAVs' drivers who are allowed to be involved in secondary driving tasks can find it hard to perform a ToC. To avoid these situations, Service 3 defines a traffic separation policy that places automated and manually driven vehicles at different lanes in order to minimize the lateral vehicle interactions at the merge area and thus reduce the number of ToCs.

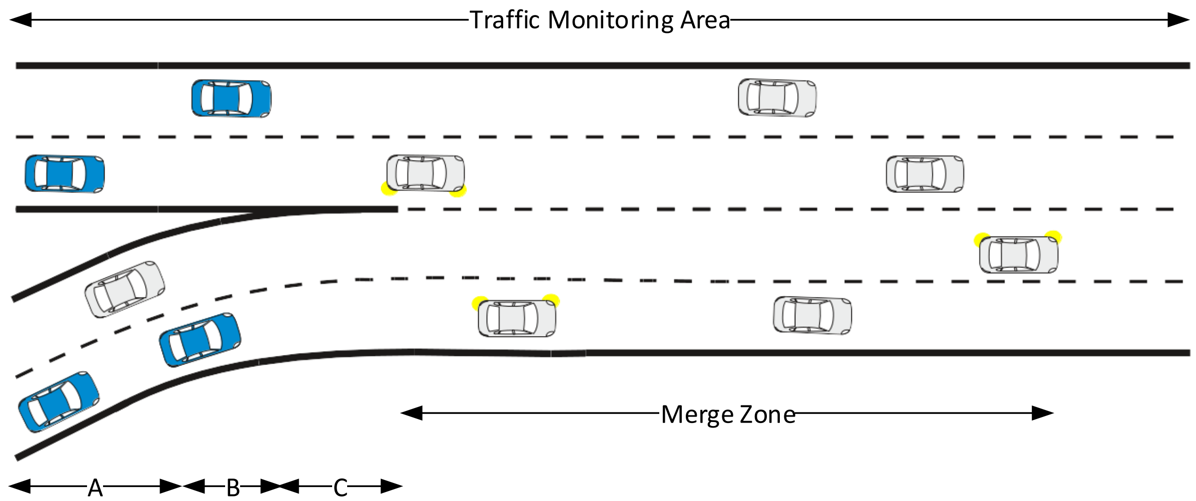


Figure 81. Scenario layout of Service 3 (A is the Traffic Separation Area, B the Transition Area and C the MRM Zone).

The traffic management logic of Service 3 is defined in the Deliverable 4.2 [5]. The TMC monitors the vehicles that enter the Traffic Monitoring Area (TMA) to determine which vehicles need to perform a lane change following the traffic separation policy. The TMC sends lane change advices to the identified vehicles that need to perform the lane change once they enter the Traffic Separation Area (zone A in Figure 81). The lane change advice includes the *triggering point of ToC* field (see Deliverable 5.1) which defines the position where the CAV should trigger a ToC if the advice has not been followed. In this scenario, the *triggering point of ToC* is defined as the start position of the Transition Area. If a CAV reaches the Transition Area (zone B in Figure 81) without performing the necessary lane change, a ToC will be initiated, and eventually an MRM at the beginning of the MRM Zone (zone C in Figure 81) if the ToC fails. This is done in order to assure that the traffic separation policy is fulfilled by all vehicles. Thus, complex interactions in the merge area between manually and automated driving vehicles are avoided reducing the risk of ToCs and/or MRMs in the merge area. Note that, a MRM in the merge area will disrupt both traffic streams. Hence, it is preferable to perform the ToCs/MRMs upstream of the merge zone to minimize the disruption of the traffic streams.

The following message flow describes the sequence of messages that need to be exchanged between the vehicles and between the vehicles and the infrastructure in order to execute Service 3 in the scenario defined in Figure 81.

Using the CAM and CPM messages shown in Section 3.2.1.1, the TMC gathers information about the vehicles approaching the highway's merge area. If the TMC finds it necessary, it sends individual lane change advices to the C(A)Vs that need to perform lane changes in order to follow the traffic separation policy (see Figure 82). The advices are sent when the C(A)Vs are entering the Traffic Separation Area. The *lane change advice* object defined in the *RSUSuggestedManeuverContainer* container of the MCM is used to send these advices. Upon the reception of the advices, CAVs use their next MCM message to acknowledge that they are going to follow the lane change advice. Those CAVs that are requested to perform a lane change are in charge of finding a gap to merge to the proper lane. If the gap is found, the CAV informs its surrounding vehicles using an MCM message that includes the updated trajectory (i.e. lane change). If the CAV is not able to find a gap by itself, a cooperative manoeuvre will be triggered by the infrastructure (centralized approach) or by the vehicle (distributed approach). Section 3.2.2 details the message flow employed for executing a cooperative manoeuvre.

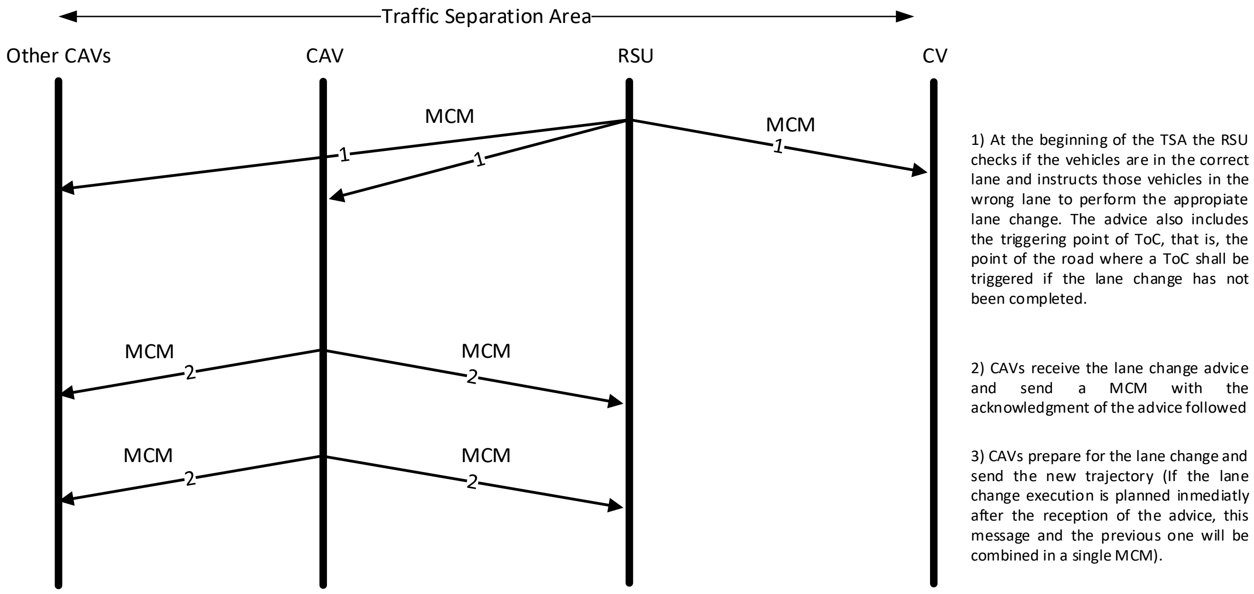


Figure 82. Message flow in the Traffic Separation Area.

Figure 83 shows the message flow in the Transition Area. CAVs entering the Transition Area but not driving in the lane assigned to CAVs will trigger a Take-over Request (ToR) to the driver of the vehicle. These CAVs will then continue driving in the same lane as manually driven vehicles. This action will trigger the transmission of an MCM message including the ToC trajectory in order to inform the surrounding CAVs and RSUs.

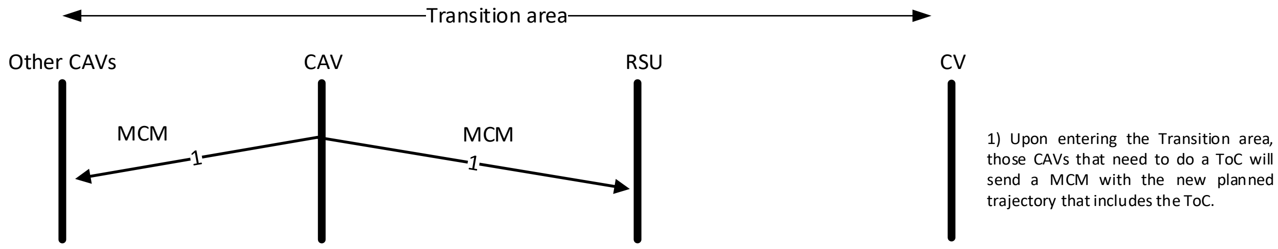


Figure 83. Message flow in the Transition Area.

If the ToC of a CAV fails, the CAV will trigger an MRM at the start of the MRM zone. The initiation of an MRM triggers the transmission of an MCM with the MRM trajectory. The TMC will be informed by the MCM of the MRM taking place. Then, it will reduce the speed limit of the scenario for the sake of safety. C(A)Vs will be informed about the new speed limit by the reception of an IVIM message. Upon the reception of the IVIM message, those CAVs that need to adapt the current speed will send an MCM with the updated trajectory.

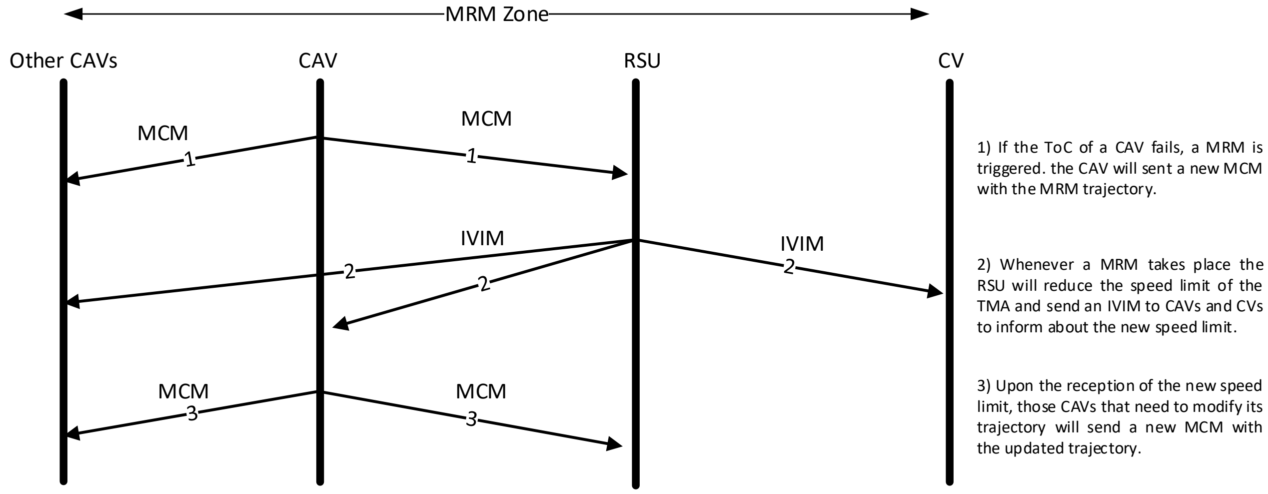


Figure 84. Message flow in the MRM Zone.

3.2.1.5 Service 4: Manage MRM by guidance to safe spot

Roadworks zones are expected to disrupt vehicle automation by inducing ToC (see Figure 85). After a ToC is triggered, the driver needs to obtain full situation awareness and then take-over the control of the vehicle. If the driver is not able to take control of the vehicle, an MRM is triggered and the vehicle will come to a full stop. In those situations, the TMC can guide the vehicles executing an MRM to a predefined safe spot in order to reduce the impact in the traffic flow and safety. In Figure 85, the critical distance indicates the minimum distance that a CAV needs to perform a lane change and an MRM before reaching the roadworks.

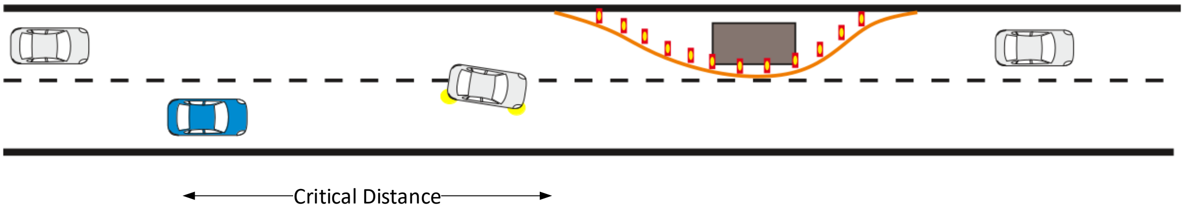


Figure 85. Scenario layout of Service 4.

The traffic management logic of Service 4 is defined in the Deliverable 4.2 [5]. In this scenario the TMC monitors the area around the roadworks zone and defines the location(s) to be used as safe spot(s). If an MRM takes place, the TMC guides the CAV to the safe spot by sending speed and lane change advices.

The following message flow describes the sequence of messages needed to execute Service 4 in the scenario defined in Figure 85. First of all, the TMC alerts vehicles upstream of the critical distance (see Figure 85) about the presence of the roadworks zone blocking the road and the existence of safe spots. This information is transmitted employing the *RoadWorksContainerExtended* container of the DENM and the MAPEM, respectively, by modifying the *LaneAttributes* of the *Road segment* of the safe spots as parking and stopping lanes. Then, the TMC monitors the scenario and looks for vehicles which need to do a ToC. The CAVs that need to perform a ToC will inform the TMC and surrounding CAVs by sending an MCM that includes the ToC trajectory. Upon reception of this MCM, the TMC will check if the CAV is in the closed lane (the lane blocked by the roadworks) or in the free lane, and if the distance between the roadworks and the CAV is sufficient to accommodate the whole ToC duration and the MRM (i.e. higher than the critical distance). If the CAV is driving in the closed lane upstream of the critical distance, the TMC will reserve the safe spot and guide the CAV accordingly if the ToC fails (see Figure 86). In case of ToC failure, the TMC will send an MCM message with a *car following advice* object as defined in the *RSUSuggestedManeuverContainer* container of the MCM. When the CAV receives the advice, it will update its trajectory. The new trajectory of the CAV is to execute an MRM that ends at the safe spot. The CAVs inform about this new trajectory by sending a new MCM message.

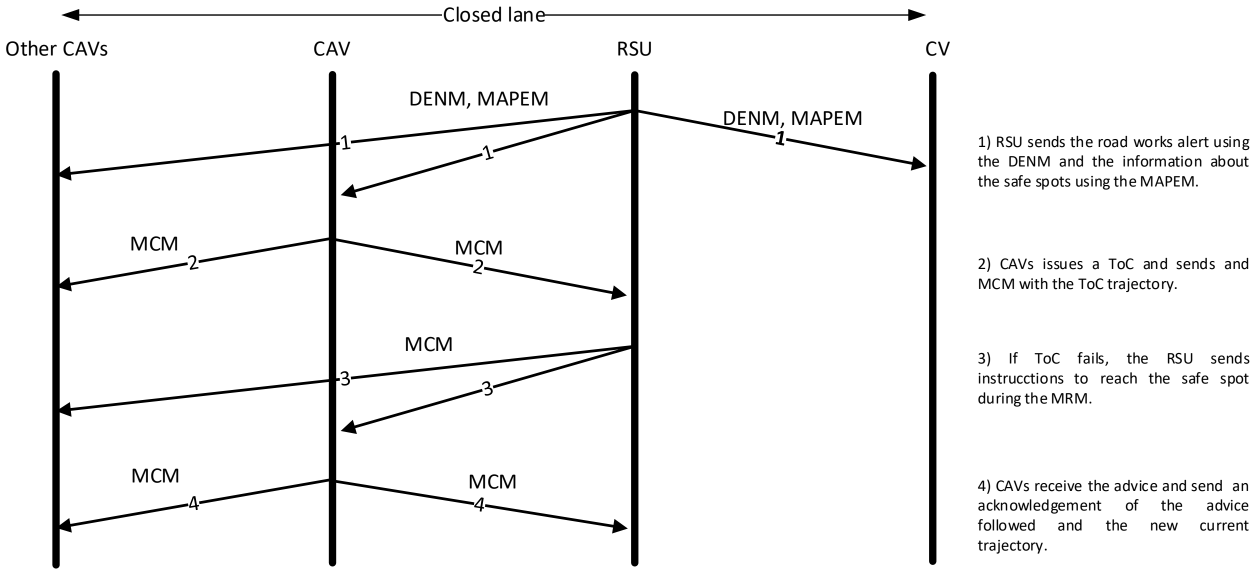


Figure 86. Message flow in the Closed lane (upstream of the critical distance).

The whole ToC and MRM cannot be performed if the distance of the CAV to the road works is shorter than the critical distance (see Figure 87). In this case if the driver does not take over control of the vehicle within a critical time window, the TMC will send an MRM advice to the CAV to ensure that there is sufficient space for accommodating the MRM in a safe way. This will be done employing the *ToC advice* object defined in the *RSUSuggestedManeuverContainer* container of the MCM.

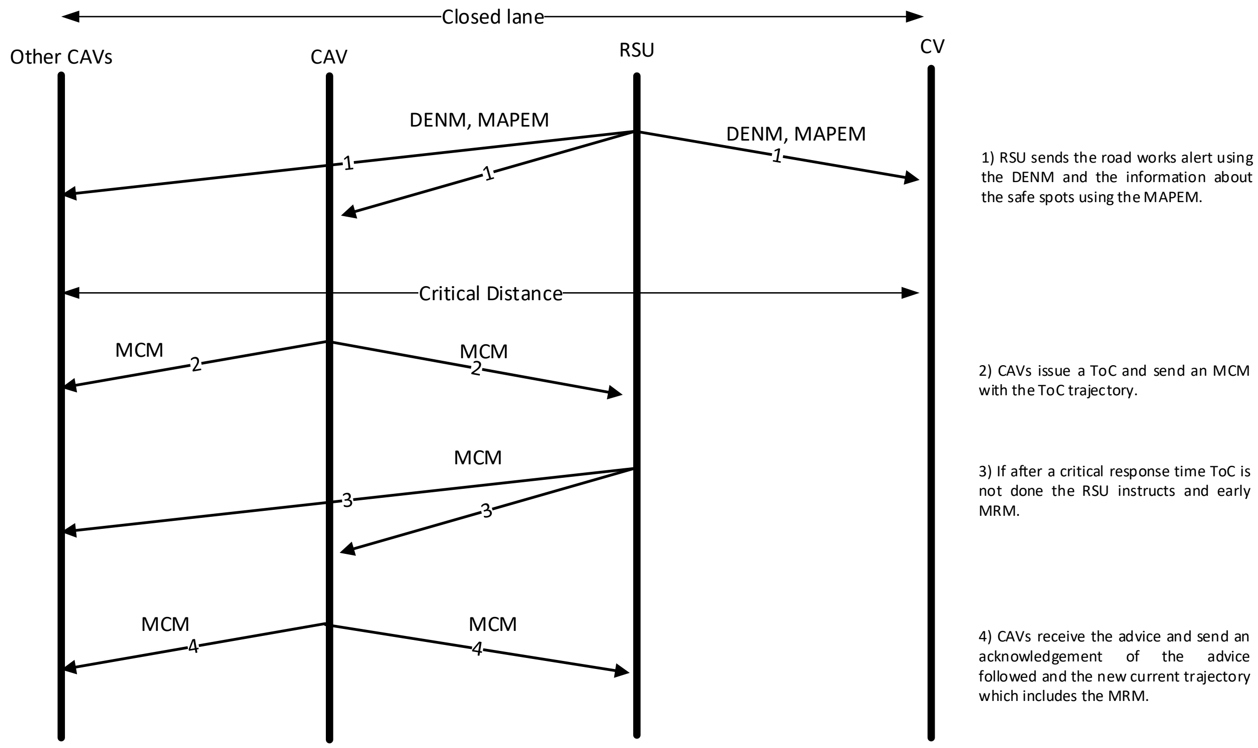


Figure 87. Message flow in the Closed lane (inside the critical distance).

When the CAV that performs the ToC is driving in the free lane upstream of the critical distance, the vehicle will need to perform a lane change in order to reach the safe spot (see Figure 88). Upon the reception of the MCM with the ToC information, the TMC will compute the trajectory necessary for the CAV to reach the safe spot. If the ToC fails, the TMC will send a lane change advice employing the *RSUSuggestedManeuverContainer* of the MCM. The CAV will receive the message and update its trajectory accordingly. This will trigger the transmission of a new MCM by the CAV which will include the acknowledgement of the advice followed and the new trajectory. If the CAV cannot execute the lane change, the TMC will check if there are nearby CAVs and it will send a *car following advice* to those CAVs in order to create a gap for the merge of the CAV performing the MRM. Again, this is done employing the *RSUSuggestedManeuverContainer* container of the MCM.

Finally, if a CAV is driving in the free lane and it is located at a distance to the roadworks shorter than the critical distance, there is no enough space for the execution of the lane change and the MRM. Thus, the TMC will not provide any advice and the CAV will perform a MRM in the free lane.

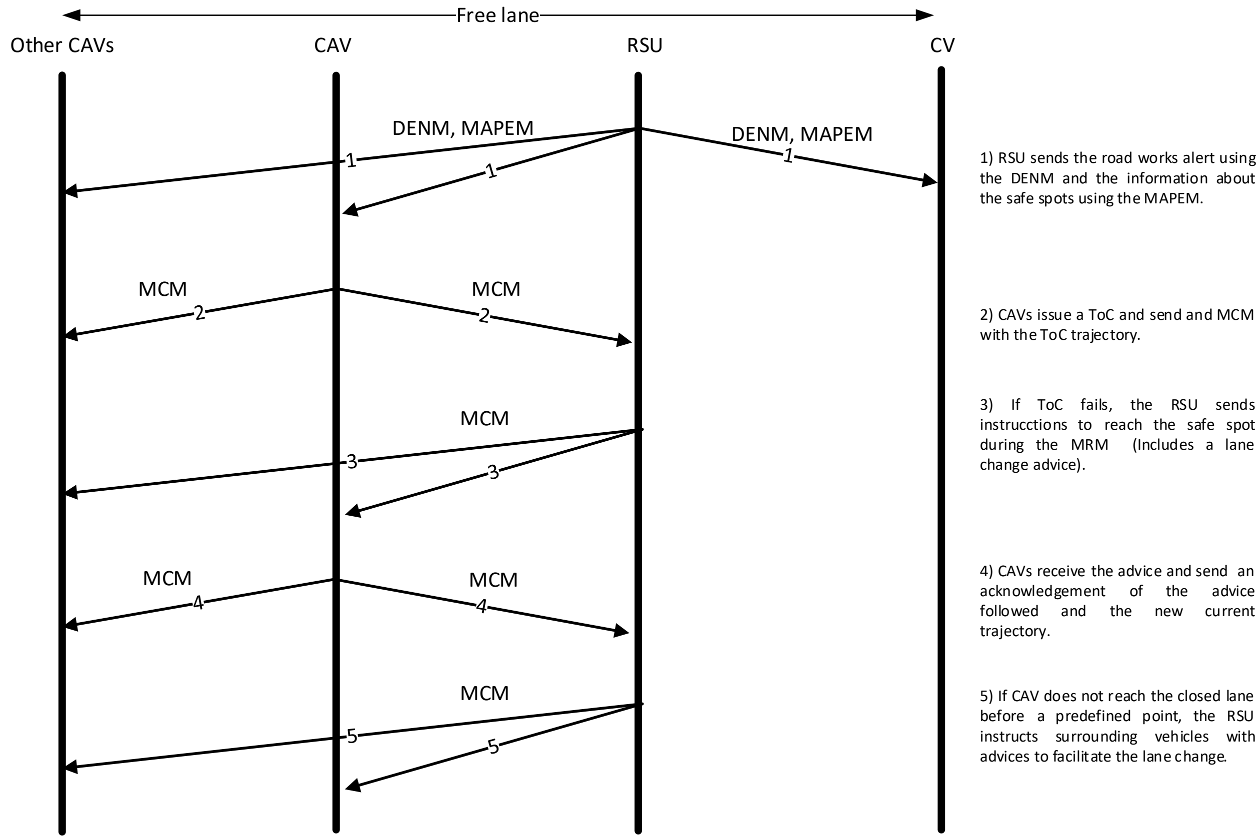


Figure 88. Message flow in the Free lane (upstream of the critical distance).

3.2.1.6 Service 5: Distribute ToC/MRM by scheduling ToCs

The automated driving is not allowed in specific traffic areas due to external reasons (see Deliverable 2.2). In these situations, CAVs must perform a ToC upstream of the No-automated-driving zone (No-AD zone) (see Figure 89). This can generate a high number of ToCs in the same area, which can lead to adverse effects for the traffic safety and efficiency. Service 5 aims at distributing the ToC in time and space over a large area in order to increase the overall traffic safety and efficiency.

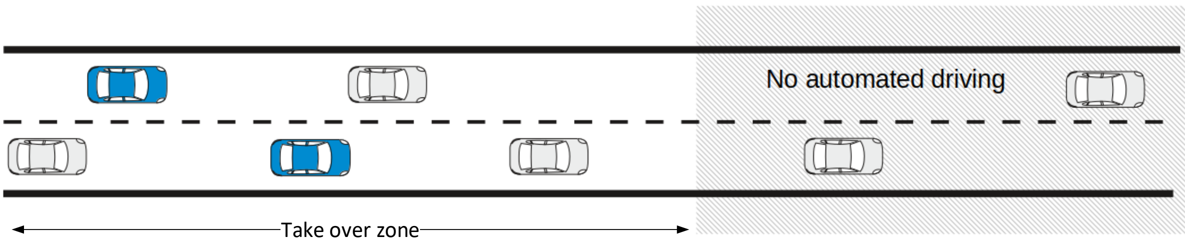


Figure 89. Scenario layout of Service 5.

The traffic management logic of Service 5 is defined in the Deliverable 4.2 [5]. In this scenario, the TMC monitors the area upstream of the No-AD-zone and computes a desirable position for the upcoming ToCs of the approaching CAVs. Using this information, the TMC sends individual ToC advices to the CAVs in order to guarantee that all CAVs are manually driving once they enter in the No-AD zone.

The following message flow describes the sequence of messages needed to execute the traffic management procedures of Service 5.

First, the TMC sends an alert to upcoming C(A)Vs to inform them about the presence of the No-AD zone. This alert is sent using the DENM message as defined in the Deliverable 5.1. Further, the TMC monitors the area upstream of the No-AD zone identifying the CAVs and computing desirable positions for the ToC of each CAV. In order to initiate the takeover, the TMC uses the MCM to send individual ToC advices to the CAVs as defined in the *RSUSuggestedManeuverContainer* container. The reception of the MCM messages triggers that CAVs execute the ToC. Also, the CAVs send an MCM that includes the acknowledgement of the advice followed and the updated trajectory. This updated trajectory includes the preparation of the ToC measures (i.e. increased headway) and the information about the ToC.

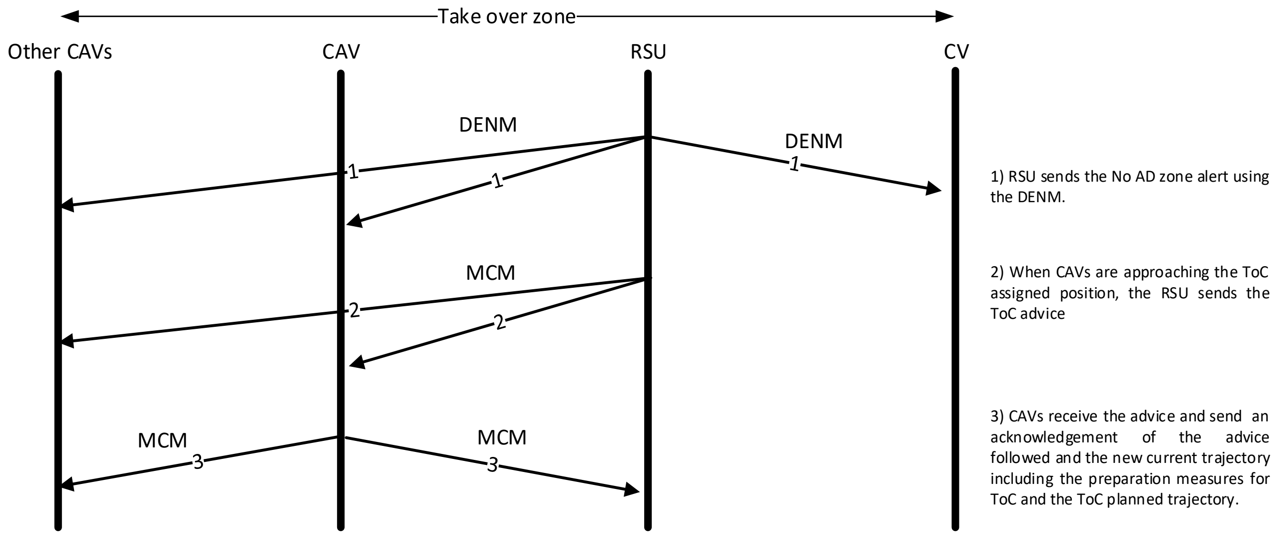


Figure 90. Message flow upstream of the No AD zone.

3.2.2 Cooperative lane changes at Transition Areas

The traffic management logic of the TransAID services requires the execution of cooperative lane changes in order to facilitate the lane change of CAVs. The execution of a cooperative lane change is based on a mutual agreement on the trajectories of different CAVs. Thus, V2X communications are necessary in order to define the cooperative trajectories of vehicles. In a cooperative lane change there are three different actors (see Figure 91): the ego-vehicle, the target leader and the target follower. The ego-vehicle is the vehicle that wants to execute the lane change. The target leader and target follower are the vehicles ahead and behind, respectively, of the CAV (i.e. the ego-vehicle) once the lane change is executed (see Figure 91). It is important to note that in the TransAID project, a cooperative lane change only modifies the trajectories of the ego-vehicles and the target follower (see the Deliverable 3.2 [61]).

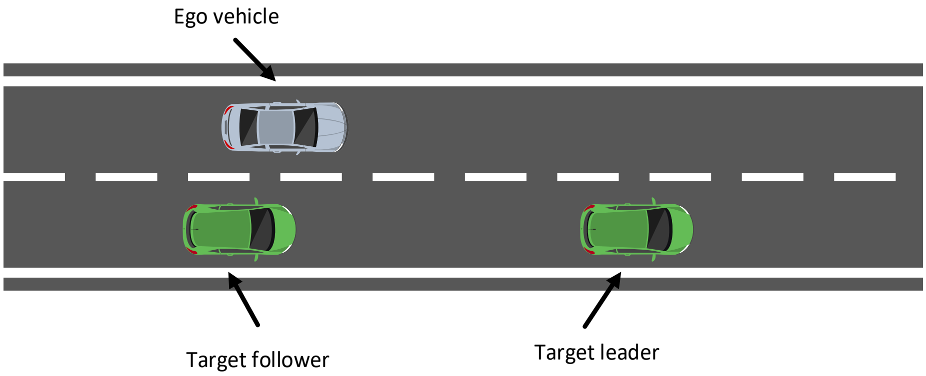


Figure 91. Cooperative lane change scenario.

The TransAID project defines two different approaches to address a cooperative lane change: centralized and distributed. In the centralized approach, the TMC manages the whole process and coordinates the trajectories of the ego-vehicle and the target follower in the execution of the cooperative lane change. Figure 92 shows the necessary message flow between the vehicles and the infrastructure in order to execute the centralized cooperative lane change. The process is based on the exchange of MCM messages between the TMC, the target follower and the ego-vehicle. First, the TMC sends a lane change advice to the ego-vehicle. If the ego-vehicle can perform the lane change advice by itself (e.g. if there is gap enough between the target leader and the target follower to allow a merge of the ego-vehicle), then no cooperation is needed. In this case, the ego-vehicle sends an MCM message that includes the new planned trajectory (i.e. the lane change) and the acknowledgement to the TMC to indicate that it is following the lane change advice. However, if it is not possible for the ego-vehicle to perform the lane change, the cooperation with other vehicles is needed. In that case, the TMC would detect that the ego-vehicle cannot perform the lane change (e.g. from the received CAM, MCM messages) and would send a gap creation advice to the target follower using the *car following advice* object defined in the *RSUSuggestedManeuverContainer* container of the MCM message. Upon the reception of the MCM, the target follower updates its trajectory in order to create the necessary gap to allow the merging of the ego-vehicle. The target follower announces the gap creation through the transmission of an MCM message that includes the acknowledgement of the advice followed and its new planned trajectory. Once the ego-vehicle detects that the target follower has created the gap, it updates its trajectory in order to perform the lane change. This lane change is announced in an MCM message that includes the new planned trajectory. Finally, the ego vehicle executes the lane change.

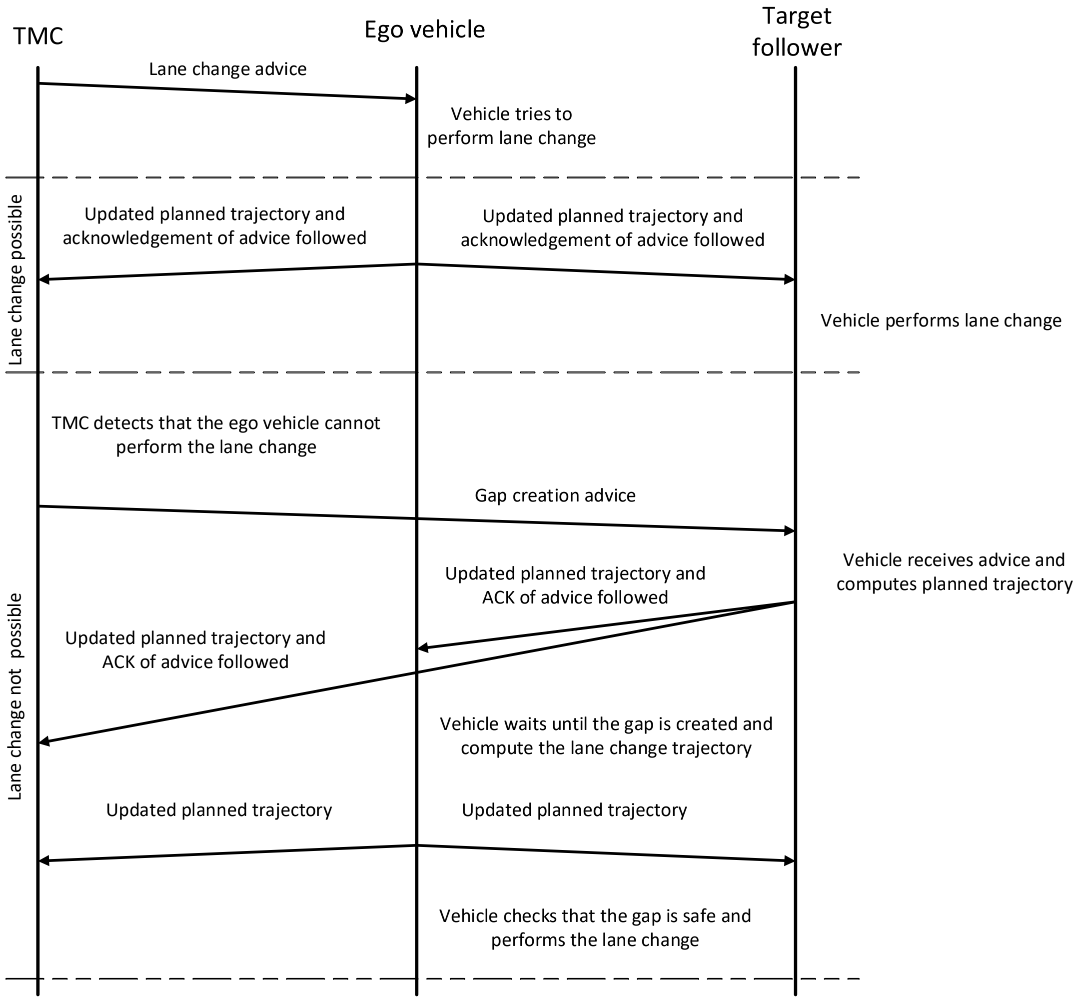


Figure 92. Message flow of a centralized cooperative lane change.

The message flow for the decentralized approach is shown in Figure 93. In this case, the cooperative manoeuvre is coordinated between the involved vehicles without the participation of the TMC. Again, the cooperative manoeuvre is triggered by the need of a CAV (i.e. the ego-vehicle) to perform a lane change. This can happen if the CAV receives an advice from the TMC or if the CAV needs to perform a lane change, for instance to overtake a slow vehicle. In the message flow depicted in Figure 93 we assume that CAV needs to perform a lane change because it has received any of the lane change advices defined in the TransAID services. Then, Figure 93 shows that the first message transmitted is a lane change advice by the TMC. However, the message flow that follows could be employed if the lane change is triggered by the ego-vehicle. Upon the reception of the lane change advice, the ego-vehicle tries to perform the lane change. If there is gap enough in between the target leader and the target follower (i.e. if it is possible to perform the lane change), the ego-vehicle sends an MCM message that includes an acknowledgement of the advice followed and the updated planned trajectory. If the ego-vehicle detects that it is not possible to perform the lane change, it will request cooperation to the other vehicles. This starts with the computation of the desired trajectory (i.e. the lane change) and the transmission of a new MCM with the planned and desired trajectories. Upon the reception of this MCM message transmitted by the ego-vehicle, the target follower updates its planned trajectory to create the gap the ego-vehicle needs to merge. The creation of this gap by the target follower would trigger the transmission of an MCM that includes its updated planned trajectory. Upon the reception of this MCM message, the ego-vehicle infers that the cooperation has been accepted and thus, it updates its planned trajectory. Again, this triggers the transmission of a new MCM message by the ego-vehicle that includes the new planned trajectory (i.e. the one that includes the lane change). Finally, once the ego-vehicle detects that the gap created by the target follower is safe it performs the lane change.

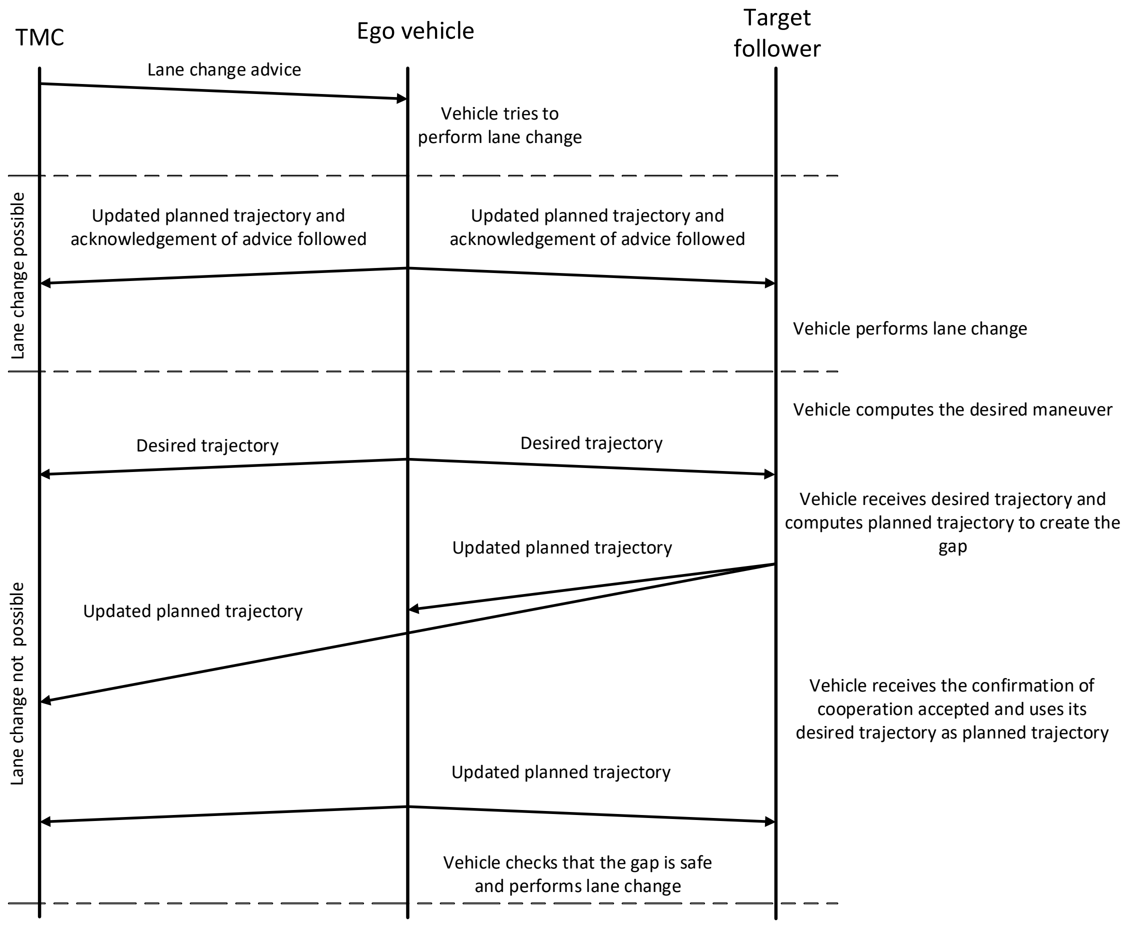


Figure 93. Message flow of a decentralized cooperative lane change.

3.2.3 Preliminary analysis of MCM generation rules

The previous sections have described the TransAID approach to coordinate manoeuvres of vehicles leveraging the support of the infrastructure, and have shown how this approach can be applied to the traffic management measures defined in the Services of the TransAID project. The TransAID approach seeks contributing to the ETSI's work item on Maneuver Coordination Service that focuses on coordinating the manoeuvres between vehicles by defining the format of the messages to be exchanged, including the MCM (see Deliverable 5.1 [4]), and their generation rules. The generation rules refer to conditions that trigger the transmission of an MCM, e.g. which vehicles should transmit an MCM and when they should transmit it. As shown in Section 2.2.2 for the collective perception service, the effectiveness of the manoeuvre coordination service highly depends on the correct design of the generation rules. In fact, MCM messages should be transmitted with a frequency high enough to guarantee that the vehicles' manoeuvre coordination is possible. However, a too frequent exchange of MCM messages can increase the channel load to the point that it can negatively impact the performance and scalability of the V2X network. The increase in the channel load can be particularly challenging if MCMs are transmitted in the reference control channel where other messages utilized to support active safety applications, such as the CAM or the CPM, are transmitted. Note that, the increase of the channel load may result in higher packet collisions and communication latency, and therefore in a reduction of the V2X reliability. These effects can in turn degrade the effectiveness of the MCS.

In this section we analyse three different generation rules for the MCM. Two of them consider a periodic transmission of the MCM at 2Hz (i.e. every 0.5s) and 10Hz (i.e. every 0.1s). The third one is a dynamic generation rule where the MCM is transmitted when the absolute position of the originating vehicle changes by more than 4m or when the time elapsed since the last transmission of an MCM is 1 second. This approach is aligned with the one currently considered at ETSI for the transmission of CAMs [14].

In order to estimate the channel load generated by the different generation rules, we follow the analytical model presented in [62] to estimate the CBR (Channel Busy Ratio), The CBR represents the percentage of time that a vehicle senses the communications channel as busy. The analytical model presented in [62] estimates the CBR as a function of the traffic density (β, in vehicles/m), the message generation frequency (λ, in Hz), the message duration (T, in seconds), and the spatial integral of the packet sensing ratio (PSR):

$$CBR = \beta \cdot \lambda \cdot T \cdot \int_{d} PSR(d) \tag{1}$$

PSR is defined as the probability of sensing a packet at a given distance. This probability is computed as the probability that a vehicle situated at a given distance from the transmitter obtains a received signal power higher than the carrier sense threshold. Equation (1) assumes that vehicles are uniformly distributed and that there are no packet collisions. Two packets collide when they are (partially) transmitted in the same time interval, thus, the amount of time that the channel is busy during a collision is lower than the amount of time required to successfully transmit two packets. Therefore, taking collisions into account would result in a reduction of the CBR estimated using equation (1). In particular, the reduction factor can range from 10% to 20% when the CBR varies from 0.3 to 0.6, approximately, according to previous studies such as [63] and [64]. Thus, the CBR estimated using equation (1) can be considered as an upper bound of the real CBR.

Figure 94 plots the CBR as a function of the traffic density per lane for the three message generation rules and for three traffic scenarios: urban, rural and motorway. The configuration parameters of the traffic scenarios (urban, rural and motorway) are extracted from the Deliverable 3.1 [65] and summarized in Table 16. For the three scenarios a straight road segment with different lanes (see Table 16) is considered. The results reported in this section also consider that the size of the MCM is 300 bytes and the size of the CAM is 200 bytes. In addition, the Winner+ B1[3] model is utilized to model the propagation losses [66]. The message generation frequency for the dynamic policy has been computed using the well-known Van Aerde model [67] that relates traffic intensity, traffic density and speed. This model has been used to obtain the relationship between the traffic density and the speed following the parameters shown in Table 16.

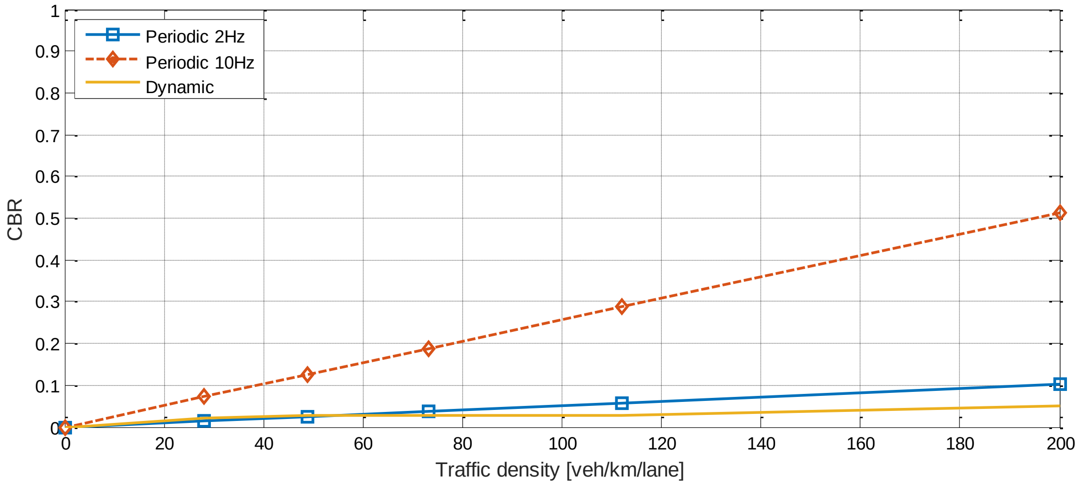
[3] The same cannel model is employed for the three traffic scenarios. Future work will take into account the effects of different channel models.

Table 16. Parameters for the different traffic scenarios

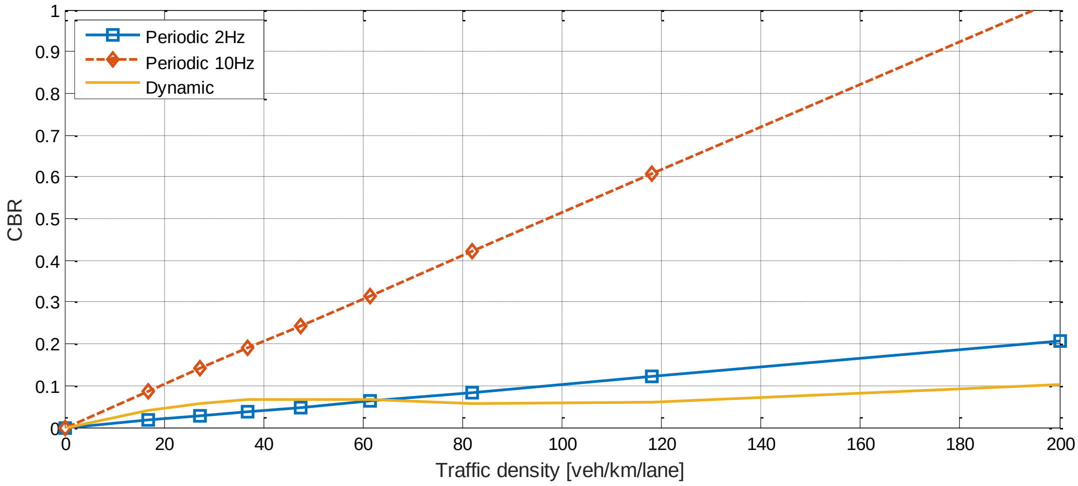
Scenario	Number of lanes	Capacity	Maximum Speed	Maximum density
Urban	1	1500 vehicles/hour/lane	50km/h	200 vehicles/km/lane
Rural	2	1900 vehicles/hour/lane	80 km/h	200 vehicles/km/lane
Motorway	3	2100 vehicles/hour/lane	120 km/h	200 vehicles/km/lane

Figure 94 shows that the periodic message generation rules do not scale well with the density since the CBR linearly increases with the traffic density. In this analysis, we compare the CBR as a function of the traffic density per lane in order to compare scenarios with a similar level of traffic congestion. It should be noted that scenarios with more lanes with the same level of congestion will accommodate a different number of vehicles. For example, a three-lane motorway can accommodate more vehicles than a one-lane urban road with the same level of congestion. If we focus on the periodic policies, the CBR increases linearly with the number of vehicles on the scenarios, thus the motorway scenario shows a higher CBR than the rural or urban scenarios. On the other hand, the dynamic policy adapts the message generation frequency to the vehicles' speed. Thus, when the traffic density per lane increases and more vehicles are transmitting MCMs, the transmission period is reduced because vehicles move slower. As a result, the CBR reduces. However, this effect stops when vehicles are moving slower than 4 m/s, at this point, the MCM is transmitted every second. If we compare the different scenarios, we can see an increase in the CBR in the scenarios with higher speeds and more lanes for two reasons: 1) there are more vehicles in the scenario and 2) vehicles move at higher speeds and thus transmit MCM more frequently. The results reported in Figure 94 show that transmitting MCM at 10Hz generates the highest channel load in the three scenarios while it is unclear whether generating an MCM every 0.5s (periodic policy at 2Hz) is sufficient for a safe and efficient coordination of the manoeuvres. The dynamic policy adapts the transmission rate to the speed of vehicles and hence it can be scaled to higher traffic density scenarios. However, as in the case of the low period approach, the dynamic policy should be carefully designed in order to fully allow the safe execution of cooperative manoeuvres.

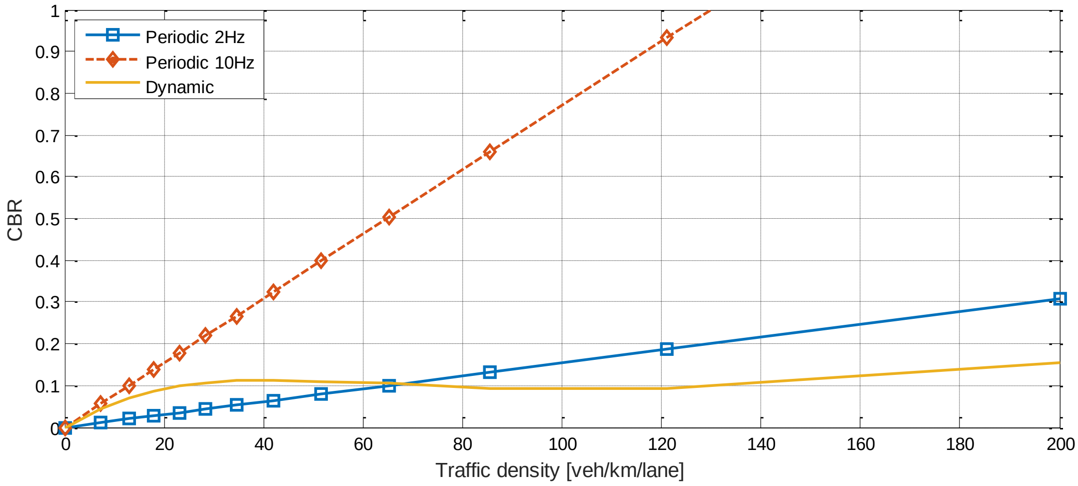
The previous analysis highlights the interest for dynamic message generation rules that take into account the vehicular context. However, further research is needed to define the message generation rules. For example, rather than continuously (with a fixed or dynamic frequency) generating MCMs, more advanced policies might also consider additional factors like the detection (through CAMs or CPMs) of a new vehicle (or object) or the anticipation of required change of trajectory. In addition, it is also necessary to analyse whether MCMs should co-exist on the reference control channel with CAMs (or beacons) and other existing messages, or whether multi-channel schemes should be considered to reduce the risk of channel congestion.



a) Urban scenario



b) Rural scenario

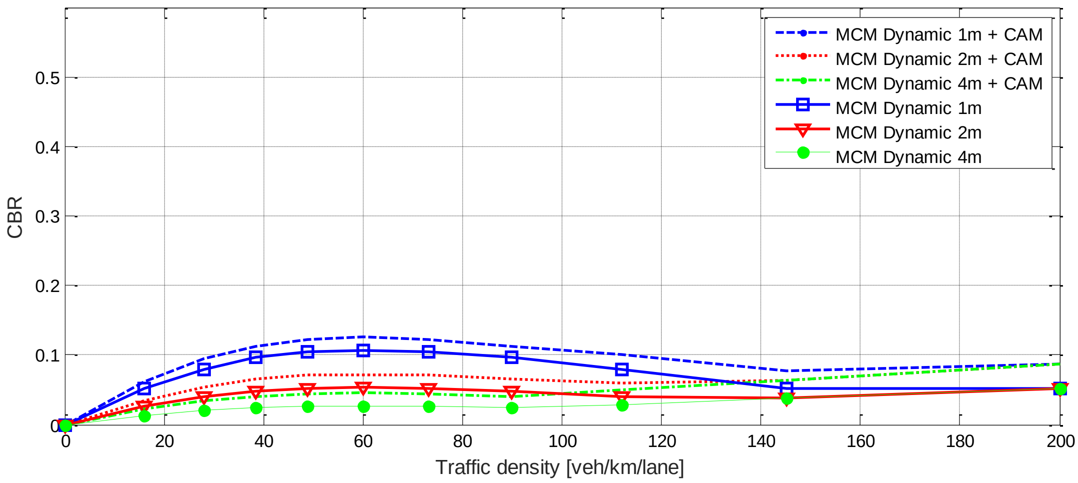


c) Motorway scenario

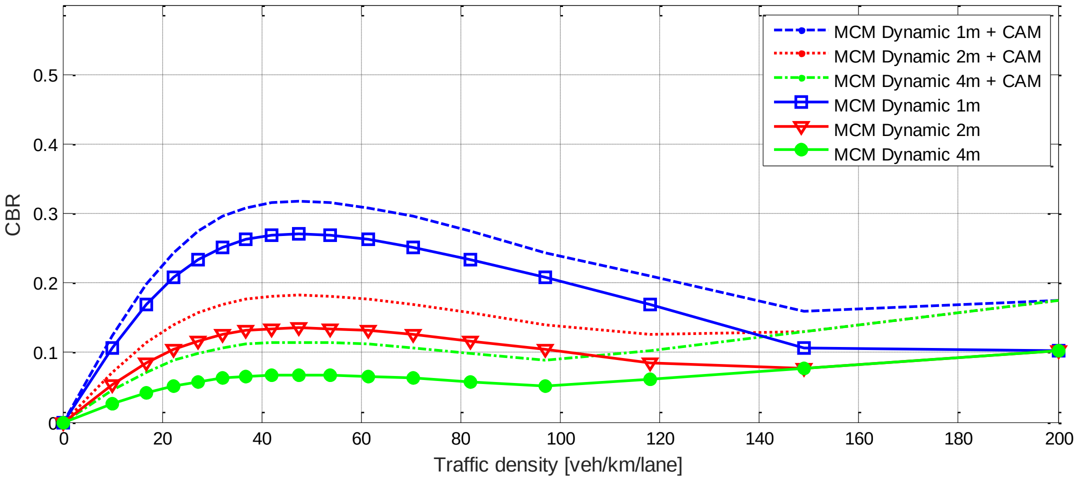
Figure 94. Channel Busy Ratio as a function of the traffic density for three different MCM generation rules (no CAM messages in the scenarios).

Figure 95 shows the CBR when the CAM and MCM co-exist in the same channel for the three different scenarios. Both the MCM and CAM generation follows a dynamic generation rule. For the CAM this policy is set as defined in the standard [14], i.e. a CAM is transmitted when the absolute position of the originating vehicle changes by more than 4m or when the time elapsed since the last CAM transmission is 1 second. On the other hand, different dynamic policies have been tested for the generation of the MCM. In particular, the MCM is transmitted when the absolute position of the generating vehicle changes more than 1m (*MCM dynamic 1m* in Figure 95) 2m (*MCM dynamic 2m* in Figure 95) and 4m (*MCM dynamic 4m* in Figure 95). Again, in all these dynamic policies the MCM is transmitted also if the time elapsed since the last MCM is one second. If we focus on the motorway scenario of Figure 95.c, we can observe how the CBR increases for the dynamic policies which transmit MCMs more frequently. Furthermore, we can also observe the increase in the channel load generated by the coexistence of CAMs and MCMs in the same channel. Similar trends are observed for the other two traffic scenarios. The coexistence of the CAM and MCM in the reference control channel can reach higher levels of channel load at higher density scenarios if the dynamic policy transmits MCM too frequent. Thus, it is necessary to further study the effects of the coexistence of messages on the same channel in terms of channel load.

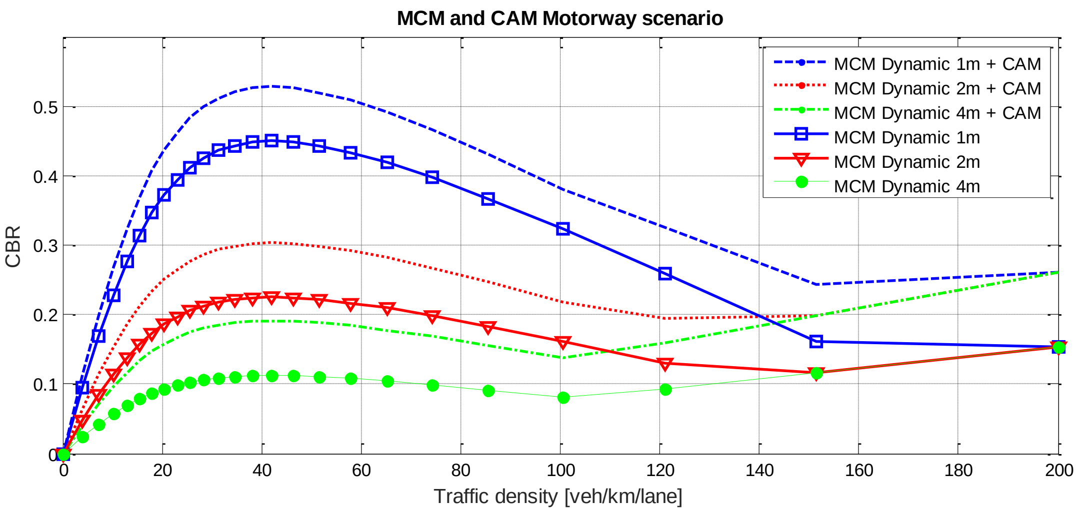
This section has shown the need to define appropriate generation rules for the Maneuver Coordination Service that allow a safe execution of the cooperative manoeuvres without compromising the wireless channel load. In the second iteration of the TransAID project we will further investigate the effects of different generation rules in the V2X communications employing advanced traffic and communications simulators such as SUMO and NS-3. Based on this analysis, an appropriate set of message generation rules will be defined in order to complete the definition of the Maneuver Coordination Service described in this Deliverable and Deliverable 5.1 [4].



a) Urban scenario



b) Rural scenario



c) Motorway scenario

Figure 95. Channel Busy Ratio for the MCM transmission on the urban, rural and motorway scenario.

3.3 Second Iteration

3.3.1 Message flow for the TransAID services

The TransAID project is defining a set of traffic management procedures and protocols to enable the smooth coexistence of automated, connected, and conventional/legacy vehicles, especially at Transition Areas. To this aim, TransAID follows a hierarchical approach that includes the implementation of control actions at different layers including centralised traffic management, infrastructure, and vehicles. In addition, TransAID has identified a set of different services and has proposed different solutions to address their Transition Areas (see Deliverable 2.2). The traffic management procedures employed for each Service rely on the communication between vehicles, and between vehicles and the infrastructure. The different messages employed by the TransAID services are defined in Deliverable 5.1. This section defines the V2X message flow between vehicles, and between vehicles and the infrastructure, that are needed to implement the traffic management procedures defined in the Deliverable 4.2 [5].

3.3.1.1 Message flow common to all TransAID services

All the TransAID services have in common the transmission of the cooperative awareness and collective perception messages that provide information about vehicles and detected objects on the road. In particular, the CAM provides status information (e.g. location, speed, acceleration, heading, etc.) about the ego-vehicle while the CPM provides information about other vehicles/obstacles detected by the ego-vehicle. Both messages must be regularly/periodically transmitted following the message generation rules defined by ETSI. The generation rules for the CAM are defined at the ETSI standard EN 302 637-2 [14]. The generation rules for the CPM are currently under standardisation [34]. The current standardization status of the CPM is described in Section 2.1.2.

The traffic management centre combines the information received in the CPM and CAM messages with other information extracted from road sensors. The fused information is used to create a virtual map of the traffic which is employed to define the traffic management procedures of the TransAID services.

3.3.1.2 Service 1.3: Queue spillback at exit ramp

The scenario of application of Service 1.3 is a two-lane motorway with an emergency and an exit lane as defined in the Deliverables D2.2 [50] and D4.2 [5]. A CAV (blue) and LVs (light-coloured) approach the exit on the motorway where there is a queue that spills back onto the motorway (see Figure 96). In the baseline scenario, vehicles are not allowed to queue on the emergency lane, but queuing on right-most lane of the motorway will cause: a) a safety risk due to the large speed differences between the queuing vehicles and the regular motorway traffic and b) a capacity drop for all traffic (including vehicles that do not wish to use the exit). The traffic management scenario assumes that the RSI will allow (and facilitate) vehicles to queue on a section of the emergency lane to avoid this capacity drop and safety risk.

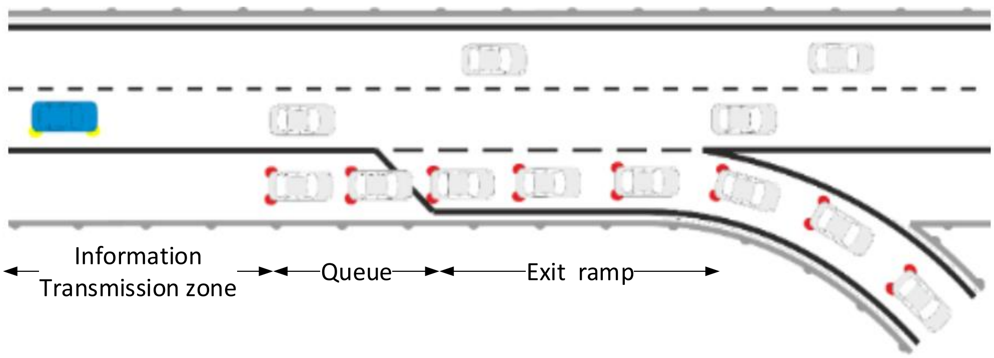


Figure 96. Scenario layout of Service 1.3.

The traffic management logic of Service 1.3 is defined in the Deliverable 4.2 [5]. The RSI will monitor traffic operations along the motorway, the off-ramp and the exit lane, and when a queue spillback is detected, a section of the emergency lane will be opened. As such, vehicles that wish to exit the motorway will be able to decelerate and queue safely without interfering with the regular motorway traffic. The length of the section of the emergency lane that is opened for traffic will be determined dynamically by the RSI. The speed limit on the main road will also be reduced to increase safety.

The execution of Service 1.3 requires the exchange of messages between vehicles, and between vehicles and the infrastructure. Figure 97 describes the message flow or sequence of messages that need to be exchanged between vehicles, and between vehicles and the infrastructure, in order to execute Service 1.3 in the scenario defined in Figure 96.

First of all, once the queue is detected, the RSI broadcasts a DENM including the alert about the queue and the position where the queue ends. If the queue spillback is detected, the RSI will also send a MAPEM with the section of the emergency lane that is opened to the traffic for queueing. Additionally, this MAPEM will also include the new speed limits defined by the RSI to increase safety and the area of applicability of these new speed limits. Upon reception of these messages, the CAVs that wish to use the exit lane will plan a new trajectory that uses the emergency lane for queueing. Those CAVs will send a new MCM including the new planned trajectory to inform other vehicles and the RSI.

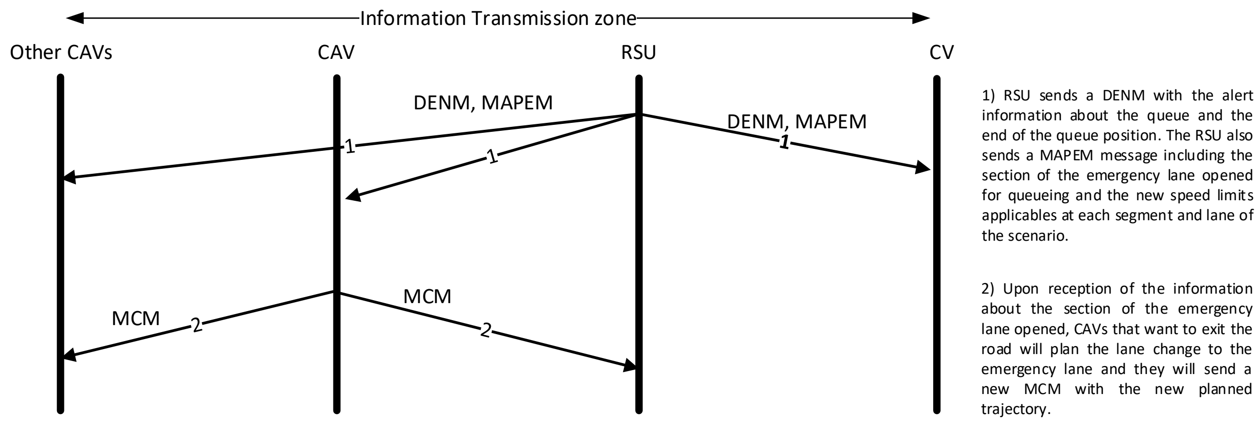


Figure 97. Message flow in the Information Transmission Zone.

3.3.1.3 Service 2.1: Prevent ToC/MRM by providing speed, headway and/or lane advice

The scenario of application of Service 2.1 is a two-lane road with an on-ramp lane on the right as defined in Deliverable D2.2. The RSU monitors the area and provides guidance to CAVs on the on-ramp lane to facilitate the merging process (see Figure 98). This is done by identifying the available gaps in the main road and providing the adequate speed advice to on-ramp CAVs in order to safely merge to the main road. If needed, speed advice will be sent to mainline CAVs in order to create gaps for the merge of on-ramp vehicles.

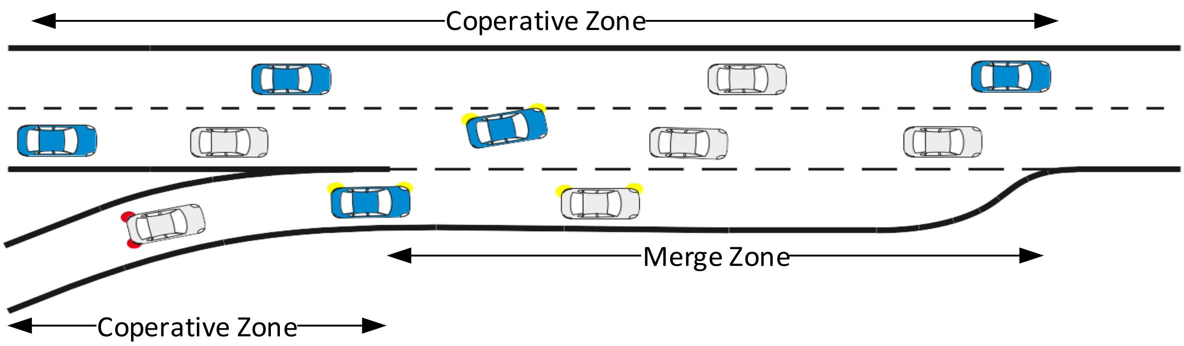


Figure 98. Scenario layout of Service 2.

The traffic management logic of Service 2.1 is defined in the Deliverable 4.2 [5]. The RSI monitors both, the vehicles coming from the (two-lane) main road, and the vehicles coming from the on-ramp road, that are approaching the merge zone. Then, the RSI computes the gaps available in between the vehicles located in the main road and evaluates whether these gaps are enough for the CAVs coming from the on-ramp lane to perform the merge. If the RSI identifies some gaps in the main road, it sends individual speed advice to the on-ramp CAVs in order to offer guidance in the merging process. For those cases in which the RSI cannot identify a gap large enough to perform the merge, the RSI will advise mainline CAVs to create a gap for the merge of on-ramp vehicles.

The following message flow describes the sequence of messages that need to be exchanged between the vehicles, and between the vehicles and the infrastructure, in order to execute Service 2.1 in the scenario defined in Figure 98.

The RSU continuously monitors the whole area and gathers information about the vehicles (i.e. speed, position, ego-lane leader gap) using the received CAM and CPM messages. With this information, the RSU detects the need to create merging gaps for on-ramp vehicles. If necessary, the RSI commands to mainline CAVs to open a gap for merging. The RSI performs this request to the C(A)Vs using the *car following advice* objects defined in the *RSUSuggestedManeuverContainer* container of the MCM. Upon the reception of this message, the C(A)Vs plan their new trajectories accordingly and send back an MCM with an acknowledgement to the RSI and the new planned trajectories. Once these gaps are calculated, the RSI sends individual speed advice to the on-ramp CAVs to facilitate the merging. Again, this is done employing the *car following advice* object defined in the *RSUSuggestedManeuverContainer* container of the MCM. Upon the reception of this advice, the on-ramp CAVs modify accordingly their trajectories. This will trigger the transmission of an MCM message that includes the new trajectory and the confirmation that the CAV is willing to follow the speed advice sent by the RSI. Finally, if the merging is not possible, the on-ramp CAVs will trigger a dynamic ToR and send an MCM with the ToC information.

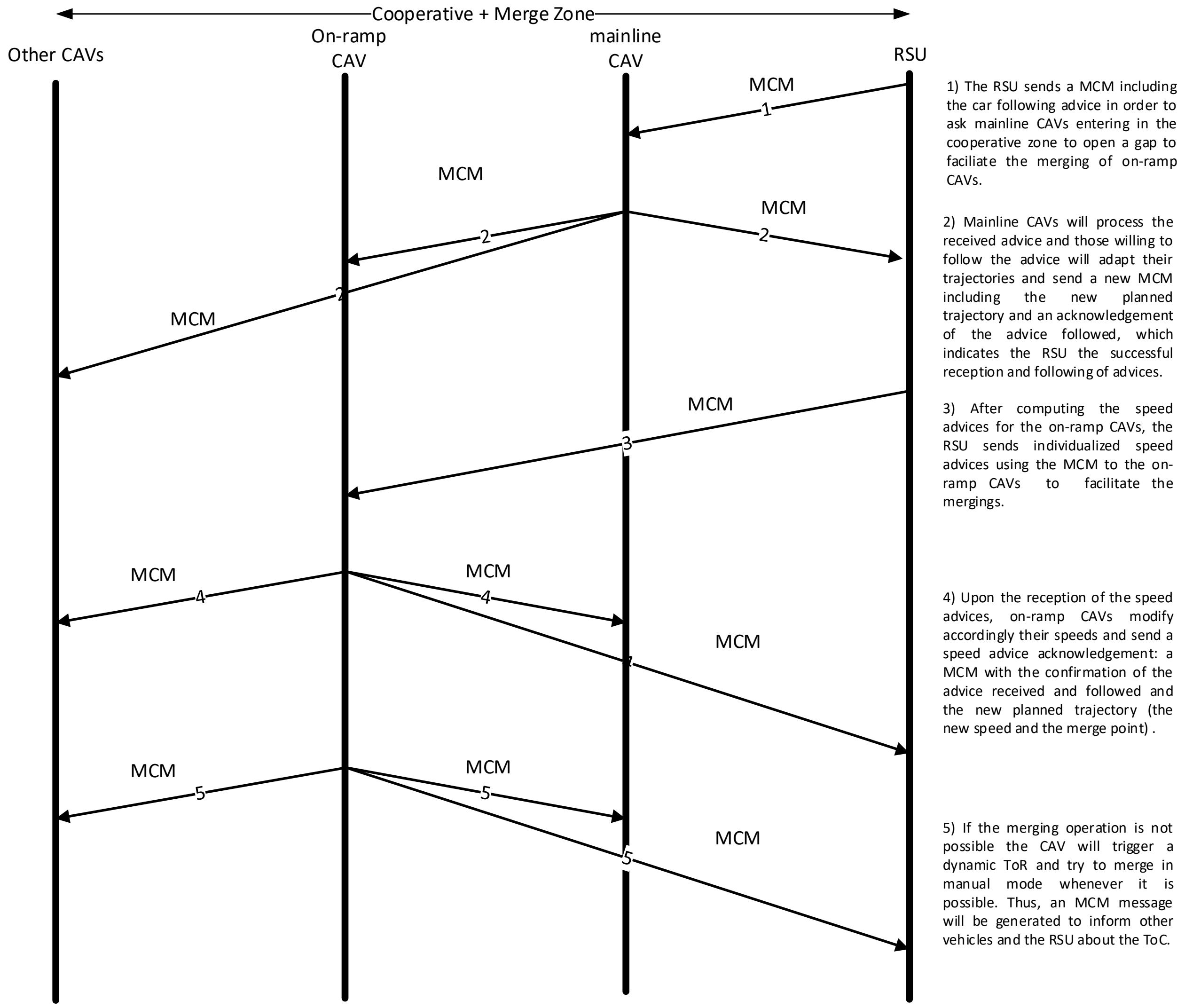


Figure 99. Message flow in the Cooperative and Merge Zones.

3.3.1.4 Service 2.3: Intersection handling due to incident

CAVs, AVs, CVs, and LVs are driving towards a signalised T-intersection (see Figure 100). Each arm of the intersection consists of two entry lanes and one exit lane. An incident occurs just before the stop line of the right turning traffic lane on the west approach (approach C, lane 5). The incident is blocking the lane 5 approximately 35 meters before the stop line and therefore vehicles driving on this lane will need to use the through traffic lane (approach C, lane 6) to drive around the incident.

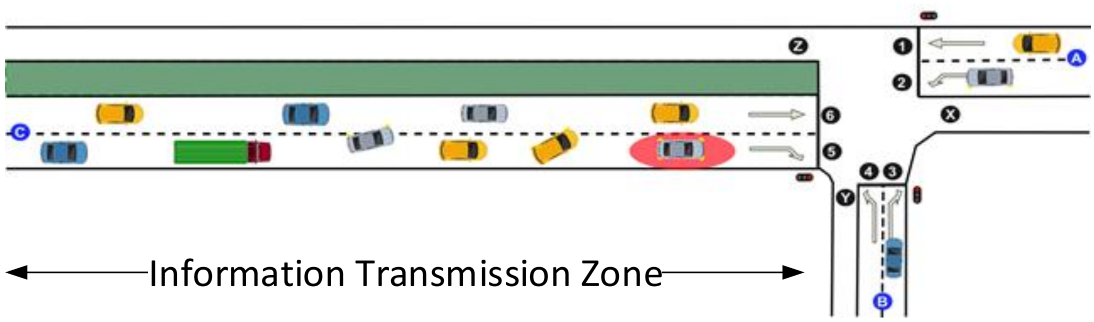


Figure 100. Scenario layout of Service 2.3

The traffic management logic of Service 2.3 is defined in the Deliverable 4.2 [5]. The RSI will monitor traffic operations along the signalised T-intersection. After the RSI detects an incident, traffic managers will firstly try to create a safe situation on the incident location. This is done by broadcasting the incident information to approaching vehicles, close the lane on the incident location, and set a temporary speed limit around the incident zone. To be able to guide automated vehicles alongside the incident and to make the right turn possible again for all the traffic lanes, usage of lane 5 and 6 are altered and the timing plan is changed to make right turns from lane 6 possible. This information is then relayed to the approaching vehicles following the timeline described in Figure 101.

First of all, the RSU will inform to all approaching vehicles about the junction topology and the traffic light information using the MAPEM and SPATEM messages. Once the incident is detected, the RSU will close the affected lanes and define new speed limits. Approaching vehicles will be alerted employing the *ADrestrictionContainer* of the DENM defined in Deliverable 5.1 [4]. Based on the received information, each CAV will decide if it is able to handle the situation. Those CAVs that cannot handle the situation will trigger a dynamic ToR and send an MCM with the ToC information. In order to facilitate the right turn for CAVs, the RSU will update the junction topology and the signal plan timing and inform vehicles using the MAPEN and SPATEM as described in Deliverable 5.1.

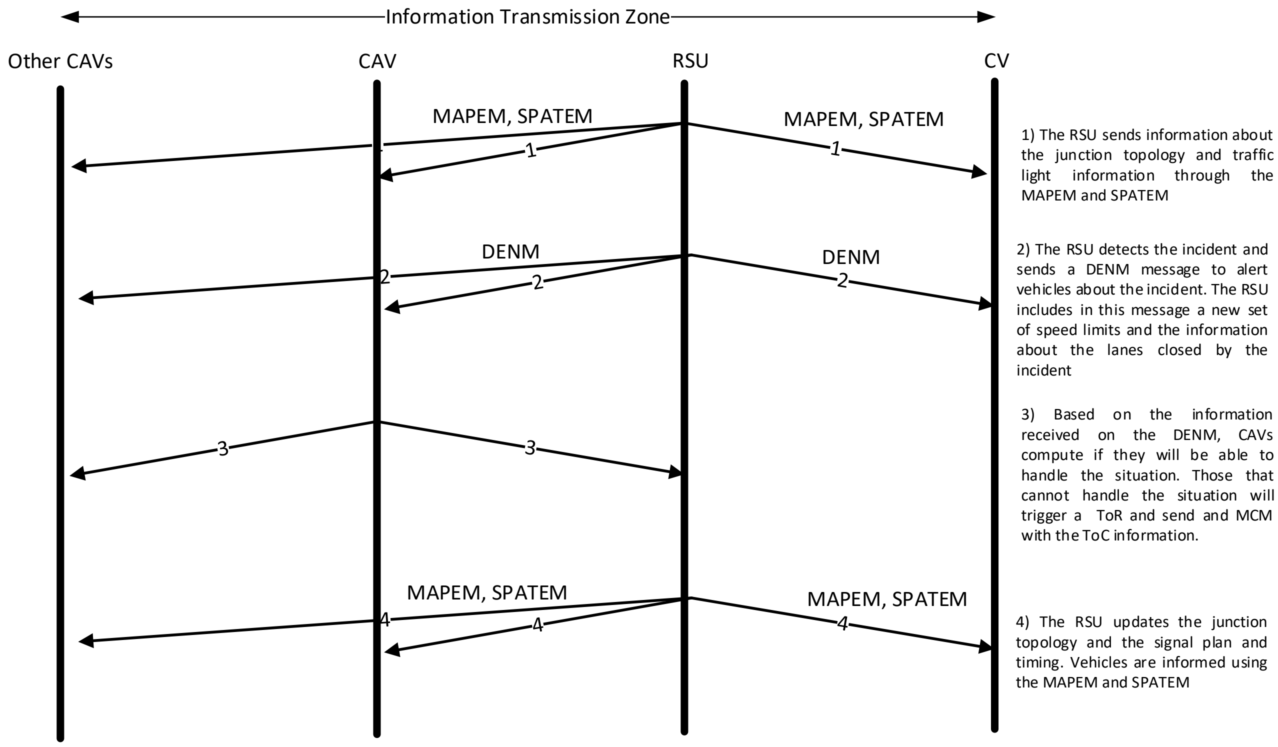


Figure 101. Message flow in the Information Transmission Zone.

3.3.1.5 Service 4.2: Safe spot in lane of blockage & Lane change assistant

A construction site is covering one lane of a two-lane road (urban or motorway). The RSI continuously collects information about the construction area and the vicinity of it and provides it to the approaching CAVs.

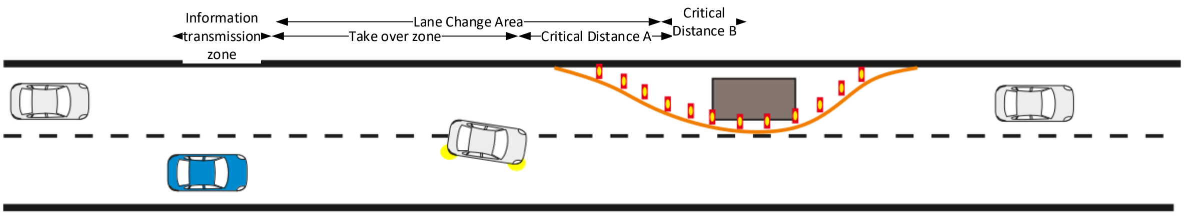


Figure 102. Scenario layout of Service 4.2.

Some CAVs are not able to pass the construction site without human intervention due to system limitations. Therefore, system-initiated ToCs take place somewhere upstream of the construction site. If any ToCs are unsuccessful, the respective CAVs perform MRMs. Without additional measures, the CAV would simply brake and stop on the lane it is driving. Thus, if it stops on the right free lane it will majorly disrupt the traffic flow, while if it stops further upstream of the work zone on the left lane it will essentially create a second lane drop bottleneck. To avoid the latter situations, the RSI which is monitoring the area just in front of the construction site, offers pre-determined spaces as safe stops to the vehicle, if they are not occupied by surrounding traffic. The CAV uses the safe spot location information to come to a safe stop in case of an MRM.

The execution of Service 4.2 requires the exchange of messages between vehicles, and between vehicles and the infrastructure. Figure 103 describes the message flow that need to be exchanged between vehicles, and between vehicles and the infrastructure in the information transmission zone. First, the RSU will alert all approaching vehicles about the road works and the lane closed due to the road works employing the *RoadWorksContainer* of the DENM. Simultaneously, the RSU will send a MAPEM message including the information of the safe spots in the area. Upon reception of these messages, CVs will trigger a ToR to manual driving and in the next transmission interval of the CAM, they will inform other vehicles about the new driving mode employing the *NewAutonomousVehicleContainer* of the CAM. Similarly, CAVs of group A that cannot handle the situation will also trigger a ToR and thus, they will send a new MCM with the ToC information.

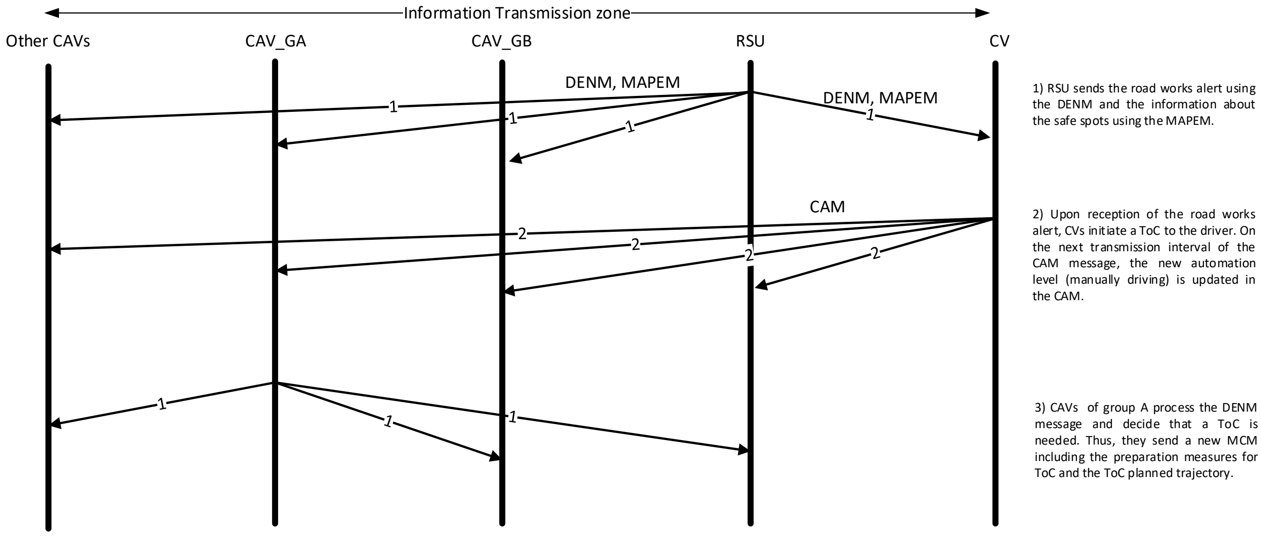


Figure 103. Message flow in the Information Transmission Zone.

CAVs of group B (the ones that can handle the situation in automated mode) will follow the message flows defined in Figure 104 when they are not surrounded by other CAVs and thus cooperation is not possible and Figure 105 when cooperation is possible. In the first case, the RSI will send to CAVs of group B driving in the blocked lane a lane change advice using the *RSUSuggestedManeuverContainer* of the MCM. Upon reception of the message, the CAVs will compute if the lane change is possible and plan its trajectory accordingly. Note that if the trajectory is changed a new MCM will be sent with the new trajectory. If the lane change is not possible the CAVs will trigger a dynamic ToR (cooperation is not possible because they are not surrounded by other CAVs) and send an MCM including the preparation measures for the ToC and the ToC planned trajectory.

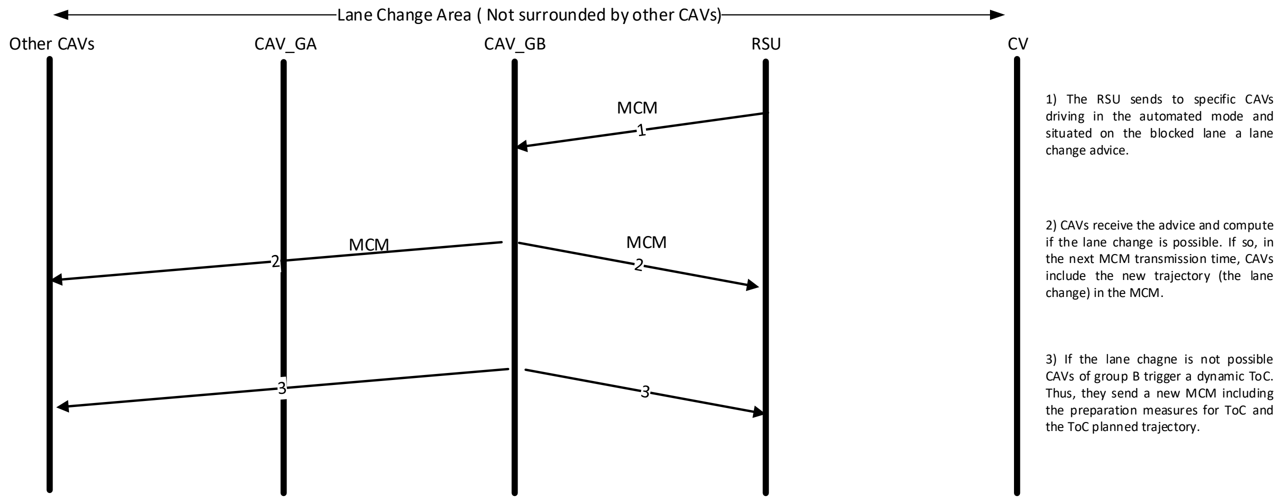


Figure 104. Message flow in Lane Change area when the CAV is not surrounded by CAVs.

In contrast, if CAVs are surrounded by other CAVs and thus cooperation is possible the following message flow will apply (see Figure 105). As before, the RSI will send a lane change advice employing the *RSUSuggestedManeuverContainer* of the MCM. If the lane change is possible, CAVs will follow the advice and plan a new trajectory to execute the lane change. This will trigger the transmission of a new MCM including the lane change trajectory. If the lane change is not possible because another CAVs possesses the right of way, the CAVs will send an MCM with a desired trajectory in order to start the cooperation. The CAV situated in the free lane (that has the right of way) receives the MCM with the desired trajectory and evaluates if it is capable and willing to accept the cooperation. In that case, the CAV will adapt its planned trajectory and send a new MCM to inform other vehicles about its new trajectory. The original CAV situated in the blocked lane receives the messages and detects that the cooperation has been accepted, thus it updates its planned trajectory with the desired trajectory and sends a new MCM. Finally, the lane change is executed. If the cooperation is not possible and the lane change cannot be done, the CAVs driving on the blocked lane will trigger a dynamic ToR and send an MCM with the ToC information.

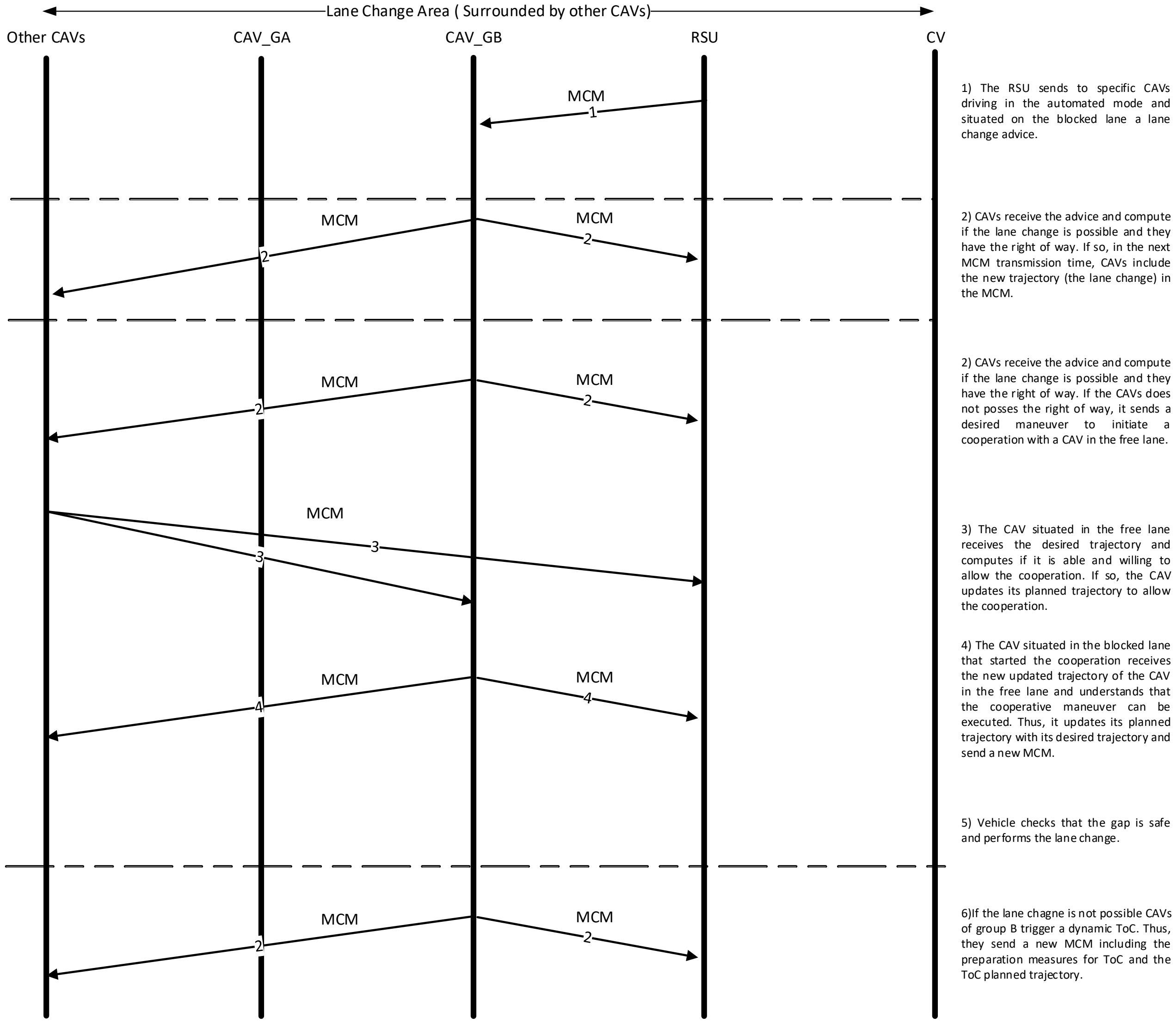


Figure 105. Message flow in Lane Change area when the CAV is surrounded by CAVs.

3.3.1.6 Service 4.1-5: Distributed safe spots along an urban corridor

On an urban two-lane road, LVs and C(A)Vs are approaching a No-AD zone, where manual driving is obligatory. Therefore, all C(A)Vs need to perform a transition, which occasionally may fail and lead to an MRM. Without further information, the vehicle would be expected to perform the MRM on the carriage way and interfere significantly with smooth and safe traffic operation. However, upstream of the No-AD zone, several parking spaces are located on the road side, which could be used as safe spots.

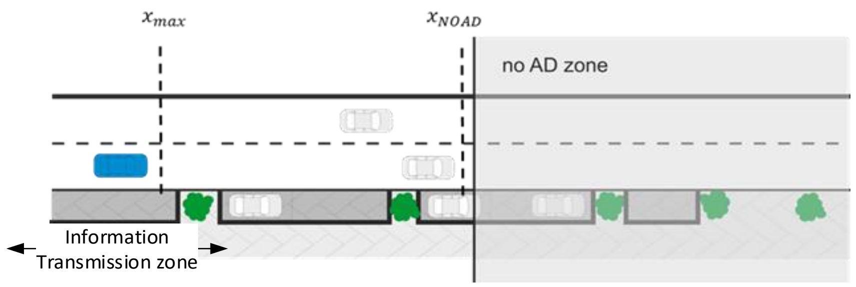


Figure 106. Scenario layout of Service 4.1-5.

The RSI monitors the position and speed of the approaching vehicles and the availability of the safe spots (parked vehicles) and provides information about which spot to use in case of an MRM to the CAVs. Further, the RSI will schedule and send ToC advices and safe spot advices to individual CAVs likely to perform MRMs. C(A)Vs that receive a ToC advice will initiate a takeover with a specified lead time. In case that the driver does not take over within this lead time the vehicle will try to steer towards its assigned safe spot and stop there.

Figure 107 describe the message flows necessary to apply Service 4.1-5 in the scenario depicted in Figure 106. First, the RSU will alert to all the approaching vehicles about the no AD zone employing the *ADrestrictionContainer* of the DENM messages as specified in the TransAID message set described in Deliverable 5.1 [4]. Simultaneously, the RSI will inform to all approaching vehicles about the available safe spots in the area employing the MAPEM message. The RSI will monitor the upcoming vehicles and whenever a likely MRM is detected it will send a safe spot advice and a ToC advice employing the *RSUSuggestedManeuverContainer* of the MCM. Upon reception of the advices, CAVs will plan a new trajectory following the received advice and will send an MCM with the new planned trajectory and the ToC information. If the ToC fails, the vehicle will trigger an MRM that will end on the assigned safe spot. This will trigger the transmission of a new MCM with the MRM information.

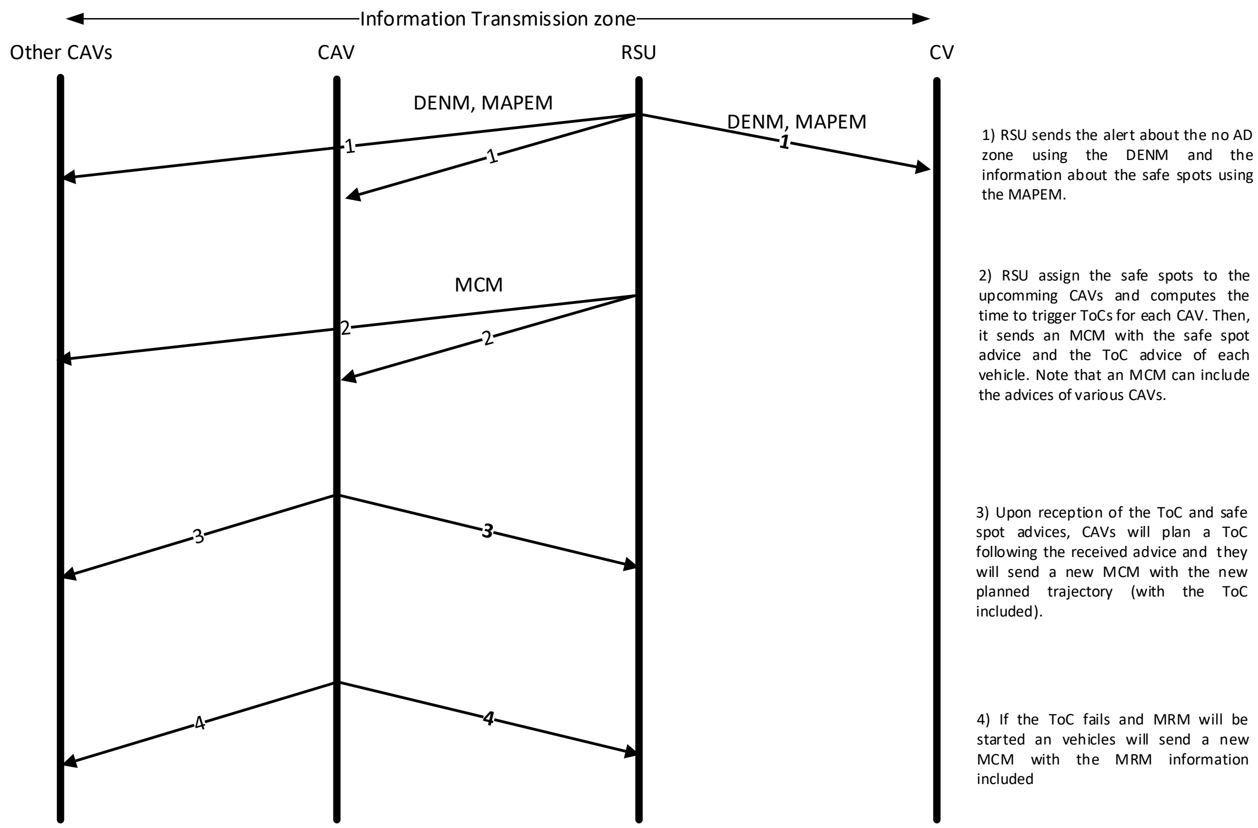


Figure 107. Message flow in the Information Transmission Zone.

3.3.2 Performance evaluation of the Maneuver Coordination Message

The standardization of a new V2X message must include the definition of a set of generation rules that describe when a new message should be generated and transmitted. The definition of these rules will affect the quality of service provided and the network load of the communications channel. The quality of service could increase with the frequent transmission of messages that update the information available at the vehicles. However, there is a limited number of messages that can be successfully delivered in a wireless communications channel and thus, it is necessary to restrict the transmission of messages to those that are needed to guarantee the minimum quality of service needed. This section reviews the different types of generation rules defined at ETSI for the CAM and CPM and proposes a novel set of generation rules for the MCM.

3.3.2.1 Review of message generation rules at ETSI

The ETSI Technical Committee on ITS has defined the generation rules for the CAM and CPM taking into account the specific needs of each service. The Cooperative Awareness service is utilized to inform other vehicles or road infrastructure nodes about the position, dynamics and attributes of the transmitting node. It should be noted that there are different CAM generation rules specified depending on whether the transmitting node is a vehicle or a RSU. In this report, we will focus on the vehicular nodes. The generation rules have been defined based on the dynamics of the vehicle transmitting CAMs. In this way, stationary vehicles will send messages less frequently while vehicles driving at high speed will send CAMs more frequently. In short, the CAM generation rules can be described as follows [14]. A CAM will be generated with a minimum frequency of 1 Hz and a maximum frequency of 10 Hz. Within these values, a CAM will be generated when one of the following conditions is fulfilled:

- The distance between the current position of the vehicle and the position included in the last CAM transmitted exceeds 4 m.
- The absolute difference between the current speed of the vehicle and the speed included in the last transmitted CAM exceeds 0.5 m/s.
- The absolute difference between the current heading of the vehicle and the heading included in the last CAM transmitted exceeds 4º.

The idea behind the definition of the CAM generation rules is to maintain neighbouring vehicles updated about the mobility of the transmitting vehicle. Thus, when the dynamics of the vehicles suffer a significant variation, a new message is transmitted to keep surrounding vehicles informed. In contrast, when the dynamics of the vehicle remain steady (and thus it can be assumed that the information available at surrounding vehicles is still valid), the frequency of the CAM transmission is reduced to efficiently employ the communication channel.

The Collective Perception Service (CPS) is employed to inform other vehicles about the objects detected by the local perception sensors equipped in the transmitting vehicle. This service allows vehicles to receive information about objects located outside their sensors' perception range. The CPM generation rules are similar to the CAM generation rules, but instead of being based on the dynamics of the transmitting vehicles, the CPM generation rules are based on the dynamics of the objects detected. A CPM will be generated with a minimum frequency of 1 Hz and a maximum frequency of 10 Hz. Within these values, a CPM will be generated whenever there are objects to be included. Objects are included in the CPM if one of the following conditions is fulfilled [34]:

- The detected object has never been transmitted in a previous CPM.
- The distance between the current position of the object and the position included in the last CPM transmitted exceeds 4 m.
- The absolute difference between the current speed of the object and the speed included in the last transmitted CPM exceeds 0.5 m/s.
- The time elapsed since the object was included in a CPM for the last time exceeds 1 s.

The CPM generation rules are defined to increase the environmental perception of surrounding vehicles. Thus, objects are included in the CPM when there is a significant change in their dynamics and thus it is required to update the information stored by neighbour vehicles. As in the CAM case, objects travelling at higher speeds will be sent more frequently while stationary objects or objects with steady dynamics will be included in CPMs with less frequency. It should be noted that the ETSI TR on CPS also includes redundancy mitigation mechanisms to reduce the channel load by avoiding transmitting redundant information, and also mechanisms that avoids the inefficient transmission of small CPMs with a small number of objects in it.

The pre-standardization study of the CACC at ETSI proposes also some modifications in the triggering conditions of the CAM sent by vehicles [70]. It offers two options for modifying the transmission frequency of the CAM. The proposal is to either fix the frequency of the CAM to 10Hz whenever the CACC is engaged or to dynamically vary the frequency between 10 Hz and 30 Hz as a function of the target time gap. Similarly, for the road side infrastructure two options are given: to set a fixed frequency of 1 Hz or to set a periodic transmission triggered by a mobile ITS station (e. g. by receiving a CAM from a vehicle).

The AutoNet2030 project also increases the maximum transmission frequency of its messages [30]. For example, the dissemination of the iCLCM is periodic with a fixed frequency of 25Hz. This high frequency is defined in order to provide reception reliability by redundancy and hence ensure reduced inter-vehicle safety distances. On contrast, the dissemination of the CLCM is not periodic but rather on demand. The dissemination of messages can be started by an originating station, which can be a RSU or an OBU on a vehicle that wants to initiate a cooperative lane change. The dissemination of CAMs is also not periodic but rather on demand. The occurrence of an event (i.e. a new vehicle wants to join the convoy or a vehicle wants to perform a lane change, etc.) will trigger the transmission of the message.

3.3.2.2 Concept proposal for MCM generation rules

The Maneuver Coordination service informs other vehicles about the future intentions of the transmitting vehicles by sending the future planned and desired trajectories. This information can be used by other vehicles in order to plan any own trajectory and avoid any possible safety conflicts by coordinating (if necessary) the trajectories of both vehicles. The definition of the generation rules must guarantee the quality of the service in all possible scenarios of application. The generation rules defined for CAM and CPM are based on the current dynamics of the vehicle/object and thus do not take into account the future dynamics (e.g. trajectories). Moreover, those generation rules only consider the own vehicle context and not the whole traffic situation. Therefore, a new set of message generation rules is required for the MCM. This new set of generation rules must assure that vehicles have updated information about the trajectories of their neighbours. Therefore, a new MCM must be transmitted whenever the planned or desired trajectories of a vehicle have significantly changed so neighbour vehicles always have reliable information. Thus, it is necessary to establish a metric to measure how two trajectories of the same vehicle differ from each other. The metric should be able to consider the difference between a vehicle that suddenly decides to execute a lane change and a vehicle that keeps driving in a straight lane with constant speed. In the first case, the neighbour vehicles must be quickly informed about the new trajectory while in the second case the urgency of updating the information at neighbour vehicles is lower because the path of the vehicle can be easily estimated from a previous stored trajectory.

It is also necessary to guarantee the possibility of coordinating the manoeuvres of vehicles in any possible situation. Whenever coordination is requested by the inclusion of a desired trajectory, the involved vehicles (i.e. the vehicle requesting the coordination and the vehicle or vehicles that are requested to cooperate) must transmit at higher rates to facilitate the coordination. Note that it is not easy to anticipate when two vehicles will need to coordinate their manoeuvres. However, we can know that whenever the trajectories of two vehicles are close to each other, a variation of one of the trajectories can generate a potential safety conflict with the other vehicle that could be solved with manoeuvre coordination. Thus, we can assume that between two vehicles there is always a potential risk of safety that depends on the trajectories of those vehicles. In some cases, this risk will be higher (e.g. when two vehicles approach the same intersection) and in other cases the risk will be lower (e.g. when two vehicles are driving in the same lane with a large headway between them). Thus, the MCM must be transmitted with more frequency when two vehicles have a higher potential risk and with less frequency when the risk is lower.

Next section describes the two metrics proposed to quantify risk between the trajectories of two vehicles and the distance between trajectories. These two metrics will be used as a basis for the proposal and analysis of different MCM generation rules.

3.3.2.2.1 Metrics

3.3.2.2.1.1 Time to risk

We describe the time to risk as a metric to quantify the risk between the trajectories of two vehicles. It is defined as the time that it will take for a specific vehicle to reach the current position of another vehicle following the shortest route between the two vehicles. Figure 108 shows an example of the computation of the time to risk in two different situations. In the first situation, the green and grey vehicles are traveling in the same direction thus, any possible risk will be determined by the relative speed and distance between vehicles. If the grey vehicle decides to do an emergency break and stop in the middle of the lane, the green vehicle will need to come to a stop before a given time in order to avoid the collision. The larger the deceleration rate of the grey vehicle, the shorter the time available for the green vehicle to stop. As the deceleration rate of the grey vehicle can be unknown to the green vehicle, we consider here the extreme case where the grey vehicle can execute an immediate stop and thus the time to risk is determined by the distance between vehicles and the speed of the green vehicle. In the other situation, the grey and red vehicles are approaching to an intersection. In this case, the time to risk is determined by the distance of the vehicles to the intersection and the speed of the vehicles.

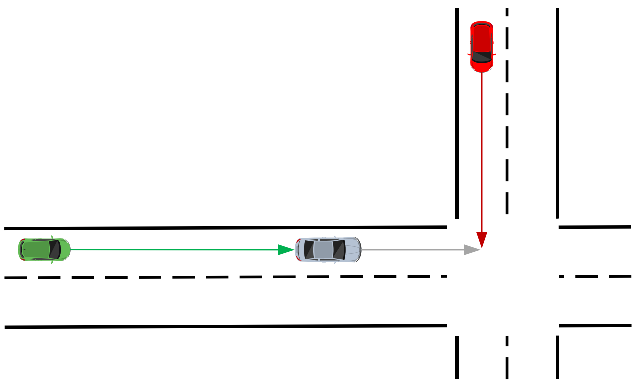


Figure 108. Example of time to risk.

The time to risk can be evaluated at any point of the trajectories. Each point i is characterized by its coordinates $(x_i \quad y_i)$ and the time the vehicle expects to reach it (t_i). The time to risk can vary in the different points of the trajectory. For example, two vehicles approaching each other will have a lower time to risk at the end of the trajectory when the vehicles are closer that at the beginning of the trajectory when the vehicles are farther away one from each other. For a specific point of a trajectory we can compute the distance between the target and ego vehicles as:

$$d_i = \sqrt{(x_i^t - x_i^e)^2 + (y_i^t - y_i^e)^2} \qquad (2)$$

where $(x_i^e \quad y_i^e)$ are the x-y Cartesian coordinates of the ego vehicle at the i-th position of the trajectory and $(x_i^t \quad y_i^t)$ the x-y Cartesian coordinates of the target vehicle at the i-th position of the trajectory. Note that this is a simplification for rectilinear roads where the Cartesian distance is equivalent to the distance over the road. For other types of roads, the computation of the distance will be different. The time to risk h_i can be computed as:

$$h_i = {}^{d_i}/_{v_i} + t_i \tag{3}$$

where t_i is the time elapsed since the start of the trajectory, v_i is the speed of the ego-vehicle if both vehicles travel in the same direction, and it is equal to the sum of the speeds of the vehicles if both vehicles travel in different directions. By adding t_i, we take into account the increment of time between the positions of a trajectory and thus the increase of the time to risk. A potential safety conflict occurring at the end of a trajectory will give the driver more time to react than the same conflict occurring at the beginning of the trajectory. As the time to risk can vary within a trajectory, we select the time to risk between a target and ego vehicle as the minimum time to risk of all the points of the trajectories of vehicles, that is:

$$\min_i h_i \tag{4}$$

3.3.2.2.1.2 Distance between trajectories

We define the distance between two trajectories as a measure of the difference between the trajectories of a vehicle. That is, whenever a vehicle decides to update its trajectory, the distance between trajectories measures the difference between the old and new trajectories. It can be defined as the maximum distance between the different points of two trajectories. Figure 109 shows an example of the distance between trajectories. In the subfigure (a) the grey vehicle detects the slow truck and decides to update its trajectory (blue trajectory) in order to overpass the truck. In order to compute the distance between trajectories, we need to compare them in the same time of reference, that is, we need to estimate where the vehicle will be at a specific time according to the old trajectory (green) and compare these positions with the ones defined by the new trajectory. With this exercise, we can know if the new trajectory is a simple continuation of the old one or if it is really a different trajectory. The subfigure (b) shows the new trajectory (blue) and the estimation based on the old trajectory (green) as a set of positions that can be compared. Finally, subfigure (c) shows the distance between trajectory points as arrows.

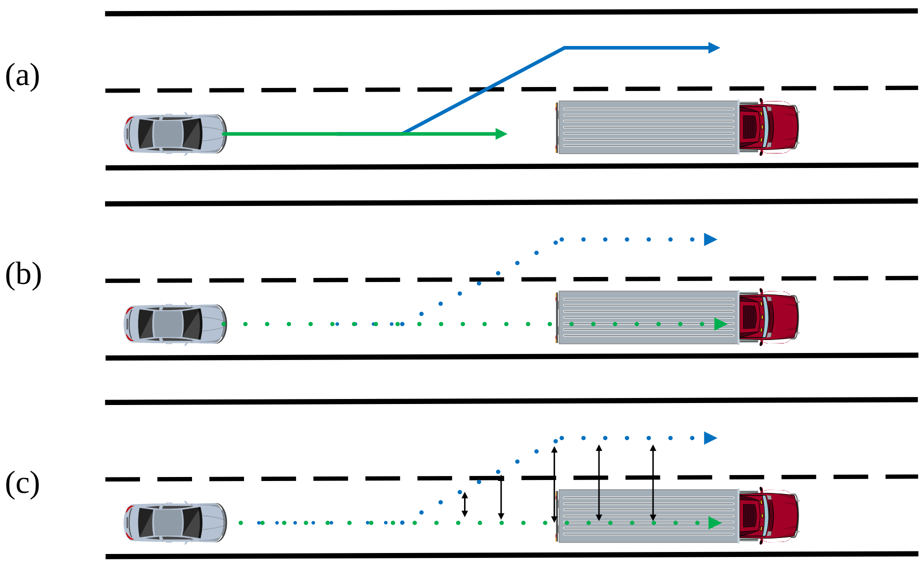


Figure 109. Example of distance between trajectories.

We can compute the distance between two specific positions of the new and old trajectories as:

$$d_i = \sqrt{(x_i^N - x_i^O)^2 + (y_i^N - y_i^O)^2} \quad (5)$$

where $(x_i^N \quad y_i^N)$ as the x-y Cartesian coordinates according to the new trajectory at the i-th time instant and $(x_i^O \quad y_i^O)$ the x-y Cartesian coordinates according to the old trajectory at the time instant i. The distance between trajectories D is computed as the maximum of the distances of all the points of the trajectory, that is:

$$D = \max(d_i) \quad (6)$$

3.3.2.3 Generation rules

Following the concepts described in the previous sections, we have defined three different policies for MCM generation rules. Common to all policies is the minimum and maximum MCM generation frequency. The MCM generation frequency defines the time interval between two consecutive MCM transmissions. The upper and lower limits of the transmission interval are set as follows:

- The MCM generation interval shall not be lower than T_GenMcmMin = 100 ms. This corresponds to the MCM generation rate of 10 Hz.
- The MCM generation interval shall not be superior to T_GenMcmMax = 1000 ms. This corresponds to the MCM generation rate of 1 Hz.

Within these limits, the generation of an MCM shall be triggered depending on the originating vehicle future trajectories and the future trajectories of surrounding vehicles. Here is where the policies differ, each policy details a different set of conditions.

First policy, from now on Risk, defines the generation rules based on the risk of the ego-vehicle with their neighbours. A new MCM must be transmitted when one of the following conditions is fulfilled:

- The time elapsed since the last MCM transmission is equal to or greater than T_GenMcmMax. This condition ensures that at least one MCM is generated per second.
- The time to risk with any of the neighbour vehicles is equal or lower than a given threshold. This condition is designed to adapt the transmission rate to the potential need of coordination with other vehicles

Second policy, from now on Risk & Dynamics, defines the generation rules based on the risk and the dynamics of the ego-vehicle. A new MCM must be transmitted when one of the following conditions is fulfilled:

- The time elapsed since the last MCM transmission is equal to or greater than T_GenMcmMax. This condition ensures that at least one MCM is generated per second.
- The time to risk with any of the neighbour vehicles is equal or lower than a given threshold and the position of the vehicle has changed by more than 4 meters since the last MCM transmitted. This condition is designed to enable the continuous transmission of MCMs without overloading the channel to inform nearby vehicles about the planned trajectory of the transmitting vehicle.

The third policy, from now on Tracking Trajectories, is based on the differences between the trajectories transmitted. A new MCM must be transmitted when one of the following conditions is fulfilled:

- The time elapsed since the last MCM transmission is equal to or greater than T_GenMcmMax. This condition ensures that at least one MCM is generated per second.

- The distance between the planned trajectory and the planned trajectory included in MCM previously transmitted is equal or greater than a given threshold. This condition is designed to immediately transmit significant changes in the planned trajectory even if they do not represent a conflict with the trajectories of nearby vehicles.

Next section analyses the effectiveness of the rules through simulations. A fourth type of periodic message rules is added as a baseline for comparison.

3.3.2.4 Analysis of MCM generation rules

The performance of MCM generation rules have been evaluated through NS-3 simulations. We have extended the NS-3 with a MCM component that implements periodic and variable MCM generation rules. Three different periodic policies with 10Hz (*T_GenMcm*=0.1s), 5Hz (*T_GenMcm*=0.5s) and 1Hz (*T_GenMcm*=1s) have been considered as a baseline in this study.

The traffic scenario is a six-lane highway with 5km length and a lane width of 3.3 meters. We simulate two different traffic densities following the 3GPP guidelines for V2X simulations [47]. The high traffic density scenario has 120 vehicles per kilometre whereas the low density traffic scenario has 60 vehicles per kilometre. The maximum speed for both scenarios is 140km/h. Vehicles created in the simulations have the dimension of 4.8m x 1.8m [33]. To avoid boundary effects, statistics are only taken from the vehicles located in the 2km around the centre of the simulation scenario. The configuration of the scenario is summarized in Table 17.

Table 17. Scenario parameters

Parameter	**Values**	
	Low traffic density	**High traffic density**
Highway length	5km	
Number of lanes	6 (3 per driving direction)	
Traffic density	60 veh/km	120 veh/km
Maximum speed	140 km/h	140 km/h

All vehicles are assumed to be equipped with an ITS-G5 transceiver (100% penetration) and operate in the same channel. The propagation effects are modelled using the Winner+ B1 propagation model following 3GPP guidelines [47]. The communication parameters are summarized in Table 18.

Table 18. Communication parameters

Parameter	Values
Transmission power	23dBm
Antenna gain (tx and rx)	0dBi
Channel bandwidth/carrier freq.	10MHz / 5.9GHz
Noise figure	9dB
Energy detection threshold	-85dBm
Data rate	6Mbps (QPSK 1⁄2)

3.3.2.5 Operation

Prior to the analysis of the performance and efficiency of the different generation rules we have performed an analysis of how the different message rules behave in order to understand its operation mechanism. Figure 110 shows the Probability Density Function (PDF) of the number of packets transmitted per vehicle for the different message generation rules policies and for two different traffic densities. We can observe how vehicles following the Risk policy transmit at maximum frequency most of the time (subfigure a). This is especially true in the high density scenario, where vehicles drive at closer distances and thus they usually fulfil the risk condition. In the opposite case, when vehicles do not fulfil the risk conditions, the transmission frequency is reduced to 1Hz. Note that vehicles cannot immediately change their dynamics and thus, when two vehicles are on risk they will maintain this condition for a certain period of time. On contrast, when vehicles are not in a risk situation it will take a while to change their relative condition. For example, a vehicle approaching another vehicle will not measure risk until it gets closer to the vehicle and then if it keeps driving at a higher speed those vehicles will be in risk until the two vehicles are far away one from each other. The Risk & Dynamics policy adds a new condition for the vehicles, so not only risk needs to be detected but the vehicle needs to move for more than 4 meters in order to transmit. Thus, the results show (subfigure b) that this policy transmits less frequently, in particular, the transmission frequency is 5 Hz in most of the cases. Note that a vehicle traveling at 140 km/h will need approximately 102 ms to move 4 meters, thus it transmission rules are checked every 100 ms (following the CAM standard definition) the condition will be fulfilled every 200 ms which corresponds to a transmission frequency of 5 Hz. If we focus on the Tracking Trajectories policy (subfigure c), we observe that the transmission frequency is 1 Hz the most part of the time. Vehicles usually drive following the same path and thus the change in the trajectories are minimal except when lane changes or larger decelerations are needed, therefore the tracking trajectories condition is not usually fulfilled and vehicles transmit at minimum frequency. The three proposed policies present different behaviour in terms of transmitted messages, while the Risk policy transmit as often as possible in most of the cases looking for the maximum information update, the Tracking Trajectory reduces the number of transmission almost to the minimum frequency aiming at an efficient use of the channel. In the middle, the Risk & Dynamics policy search for the trade-off between the update of information and the efficient use of the channel. Next section analyses the impact of these policies in the communications channel and the performance of the MCS.

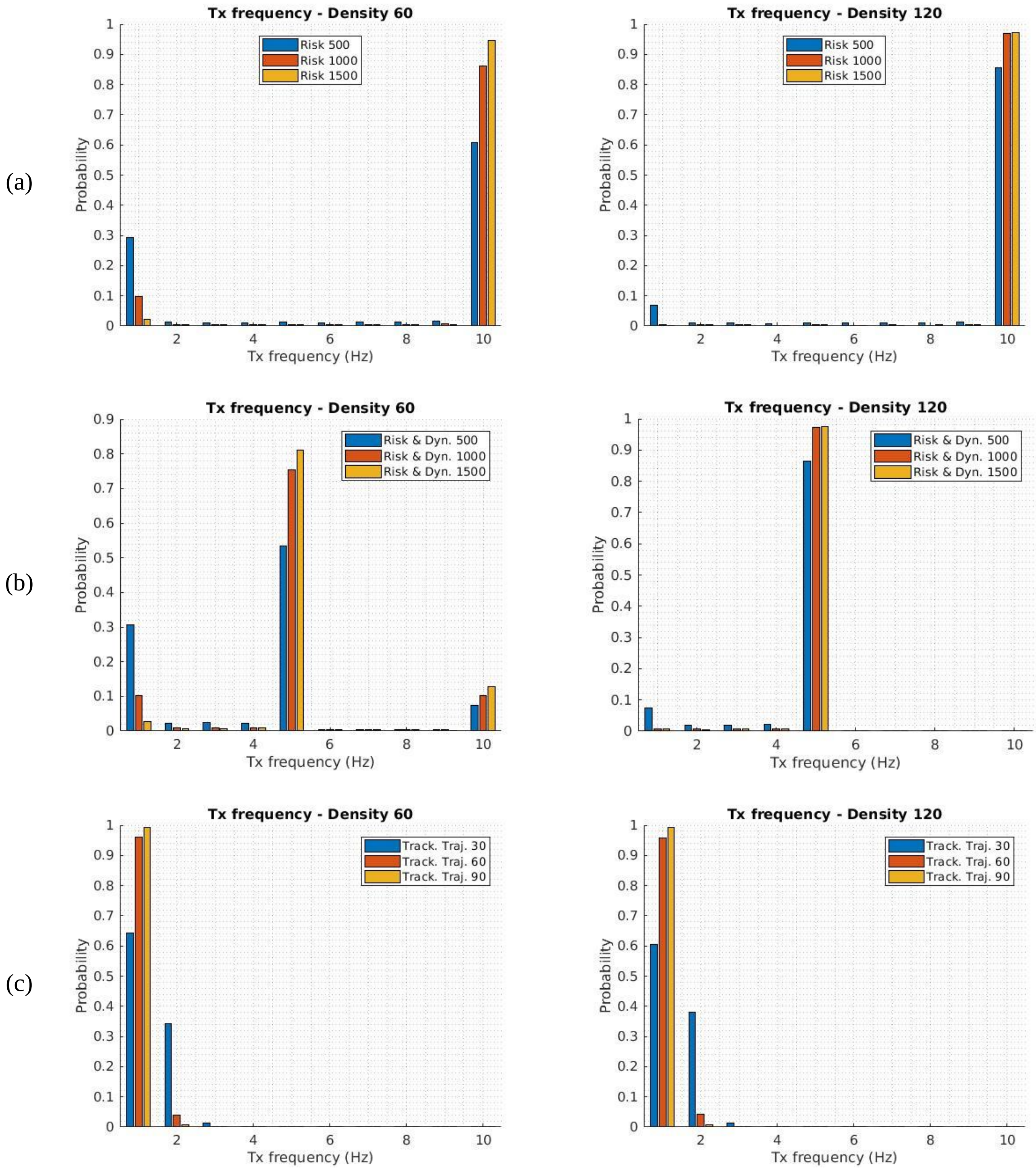


Figure 110 PDF (Probability Density Function) of the number of MCMs generated per second and per vehicle for each policy

3.3.2.6 Communications performance

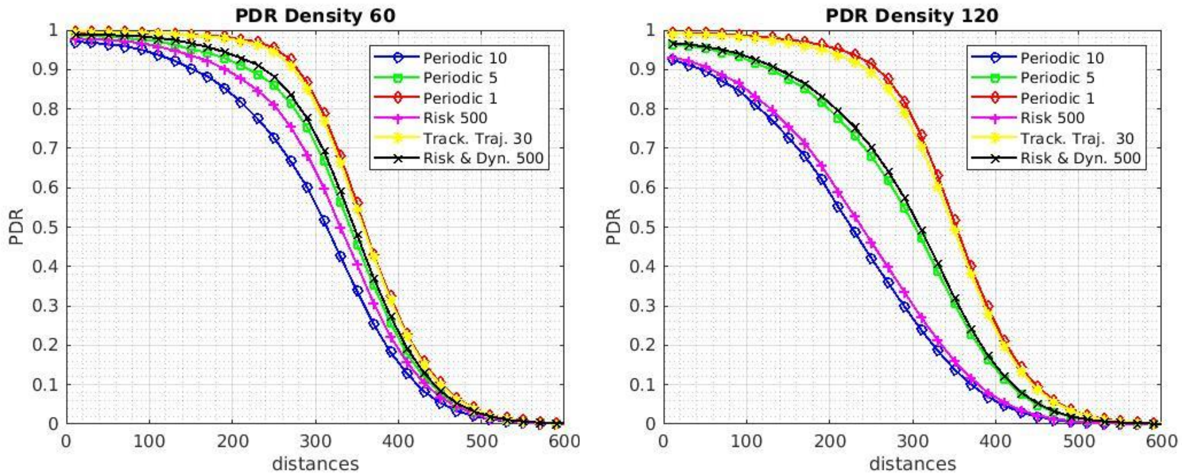
This section evaluates the impact of the different MCM generation rules policies on the communications performance. To this aim, Table 19 shows the average channel busy ratio experienced when implementing each MCM generation policy under the two traffic densities. The CBR is measured by each vehicle every second. The CBR is a measure of the channel load, and it is defined as the percentage of time that the channel is sensed as busy. A high CBR value indicates that the channel is very loaded and hence risks saturating. If this happens, the communications performance degrades and the packet delivery ratio decreases [49]. As expected, the CBR for the periodic policy increases with the frequency, the higher the number of packets transmitted, the higher the percentage of the time that the vehicles sense the channel as busy. The CBR of the Risk policy is similar to the CBR obtained by the periodic policy at 10Hz, this is the expected behaviour because the risk policy usually transmits at 10Hz as seen in Figure 110. Both policies have a high rate of channel usage which can lead to congestion and multiple packets drops which will decrease the performance of the maneuver coordination service. In contrast, the Risk & Dynamics policy reduces the usage of the channel by adapting the transmission rare to the dynamics of the transmitting vehicles. As shown in Figure 110 this leads to a decrease of the number of transmitted messages and thus a lower CBR is obtained. Similar CBR values are obtained by the Risk & Dynamics policy and the Periodic 5 Hz policy. Again this is the expected behaviour because the Risk & Dynamics policy transmit at 5Hz most of the time (see Figure 110). The Tracking Trajectories policy presents the lower percentage of CBR. Note that in this policy, messages are transmitted only when there are significant changes in the trajectory sent and therefore it minimizes the number of transmitted messages.

Table 19 Average CBR (Channel Busy Ratio)

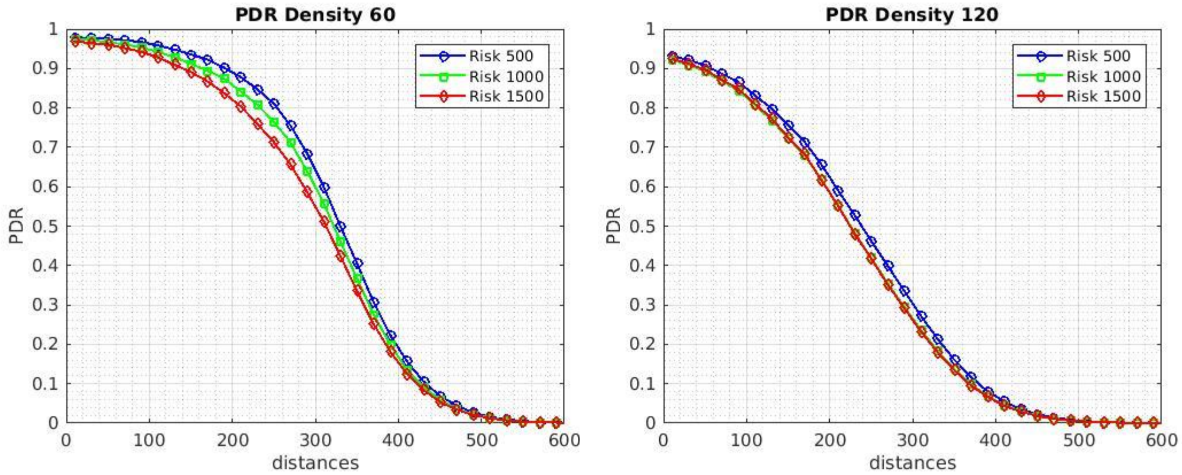
Policy	Threshold	CBR	
		60 veh/km	120 veh/km
Periodic	10 Hz	27%	52.2%
	5 Hz	14.3%	29.3%
	1 Hz	3.4%	6.8%
Risk	500 ms	19.6%	49%
	1000 ms	24.9%	52%
	1500 ms	26.4%	52.1%
Risk & Dynamics	500 ms	12%	27.4%
	1000 ms	14.8%	29.4%
	1500 ms	16%	29.3%
Tracking Trajectories	30 cm	4.4%	9.2%
	60 cm	3.5%	7%
	90 cm	3.4%	6.8%

The channel load has an impact on the successful transmission of messages. The Packet Delivery Ratio (PDR) is defined as the probability of successful reception of packets. Figure 111 depicts the PDR as a function of the distance between the originating and receiving vehicles. The PDR decreases with distance due to the radio propagation effects. Further, the PDR can also be degraded due to packet collisions or interferences. This effect can be shown focusing on the periodic policies of Figure 111, as the transmission rates increases, the PDR decreases due to a higher number of packet collisions and higher interferences. If we compare the different generation rules policies between them (subfigure a), we can observe that the Periodic 10 Hz policy obtains the lowest PDR for the two traffic densities closely followed by the Risk policy. This is especially true for the high traffic density scenario where the Risk and PDR 10 Hz policies show a similar PDR curve. The Risk & Dynamics policy improves the PDR for both traffic densities because it is able to adapt the transmission rate to the dynamics of vehicles reducing the amount of transmitted messages. On the other hand, the Tracking Trajectory policy obtains a higher PDR similar to the Periodic 1 Hz. This policy shows the most efficient use of the channel in terms of communications as it only transmits when the difference between the transmitted trajectories is significant. It is still needed to evaluate the efficiency of the metrics in terms of manoeuvre coordination parameters and not only in communications terms. If we compare the different thresholds applied to the policies, we can observe that there are not significant changes in the PDR by the variation of the thresholds employed. Only the Risk policy presents different PDRs in the low traffic density scenario (subfigure b). As expected, the PDR increases when the risk threshold is increased because less packets are transmitted and the CBR is lower as seen in Figure 110 and Table 19.

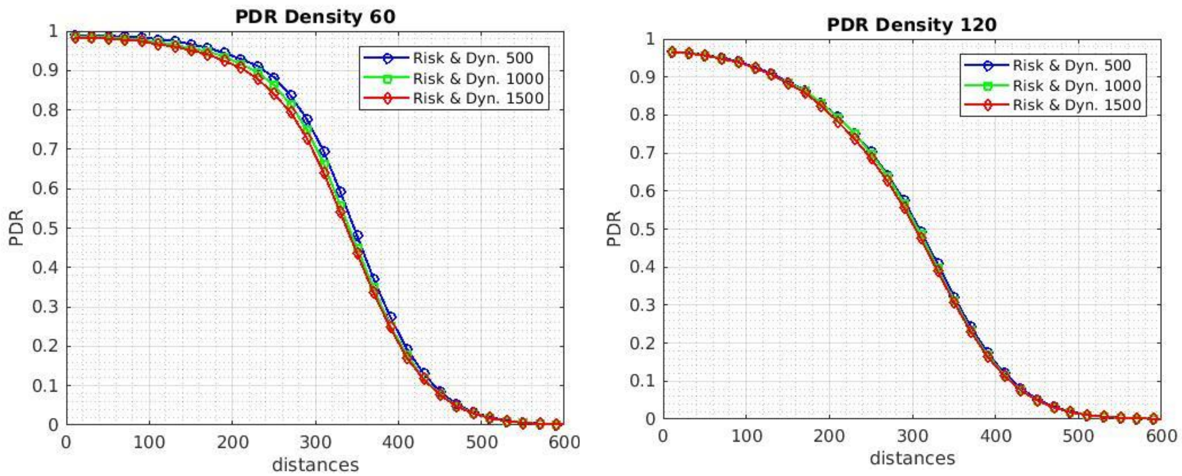
(a)


PDR Density 60
Periodic 10
Periodic 5
Periodic 1
Risk 500
Track. Traj. 30
Risk & Dyn. 500
PDR
distances
PDR Density 120
Periodic 10
Periodic 5
Periodic 1
Risk 500
Track. Traj. 30
Risk & Dyn. 500
PDR
distances

(b)


PDR Density 60
Risk 500
Risk 1000
Risk 1500
PDR
distances
PDR Density 120
Risk 500
Risk 1000
Risk 1500
PDR
distances

(c)


PDR Density 60
Risk & Dyn. 500
Risk & Dyn. 1000
Risk & Dyn. 1500
PDR
distances
PDR Density 120
Risk & Dyn. 500
Risk & Dyn. 1000
Risk & Dyn. 1500
PDR
distances

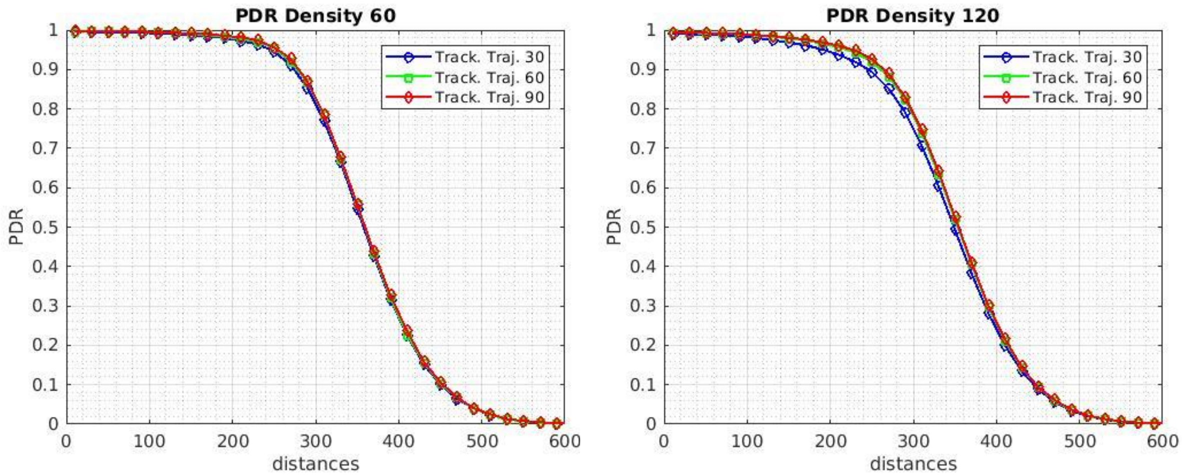
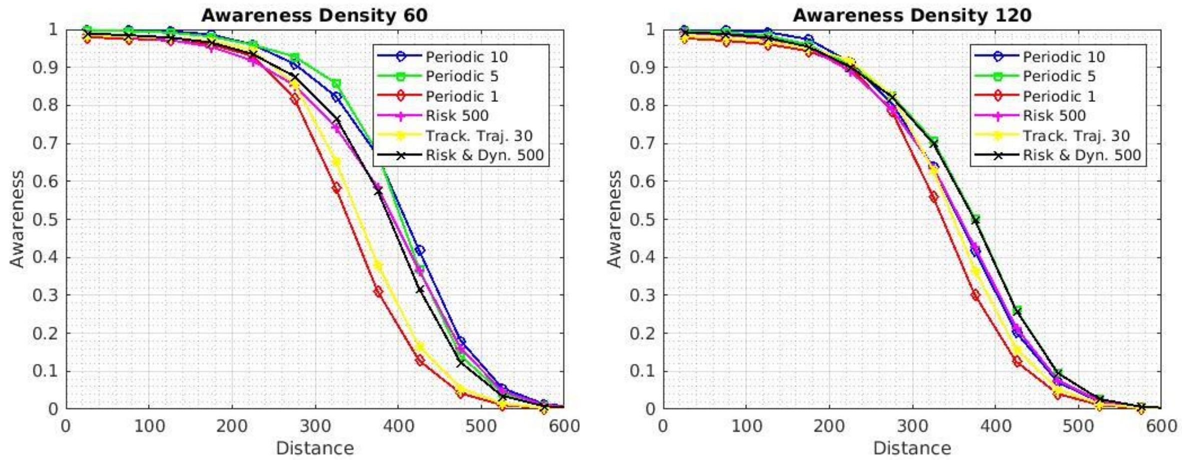
(d) 

Figure 111 PDR (Packet Delivery Ratio) for the MCM generation rules policies evaluated on two different traffic densities

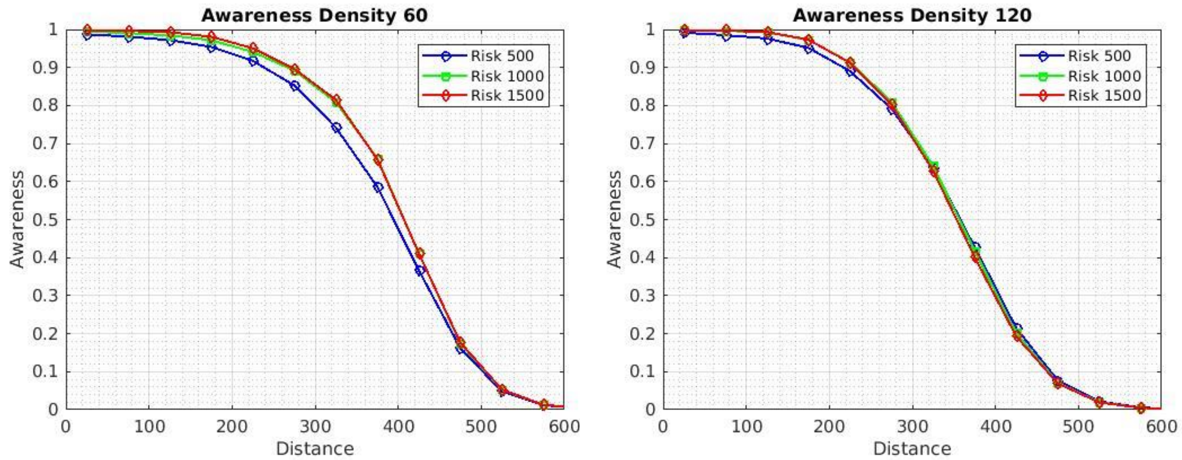
3.3.2.7 Manoeuvre Coordination performance

The analysis of the performance of different generation rules policies needs to take into account the efficiency of the policies from an application layer point of view. One of the questions to answer is if vehicles are aware of other vehicle's manoeuvres. The knowledge about other vehicles intentions is the basis for any possible manoeuvre coordination. Note that vehicles need to estimate other's vehicles trajectories in order to define its future motion plan. This knowledge can be measured using the awareness metric. This metric measures the ratio of vehicles in a specific range from which a message has been received in a given time interval. In other words, it measures the ratio of neighbour vehicles inside a range from which the ego-vehicle has knowledge about their trajectories. Figure 112 shows the awareness as a function of the distance for the different generation rules policies and traffic densities within a time interval of 1 second. We can observe how the different policies show a high awareness (over 90%) rate up to 200 meters for both traffic densities (subfigure a). Whenever packet errors are mainly caused by the propagation losses, policies that transmit more frequently will show higher awareness even at larger distances. This can be observed comparing the Periodic 1 Hz and Periodic 5 Hz policies which present respectively the lowest and highest awareness for both traffic densities. However, if we keep increasing the transmission rate, the packet losses will be also caused by packet collision and interferences, thus increasing the transmission rate will not be beneficial anymore and can even drop the awareness as in the case of the Periodic 10 Hz policy at the high density scenario. A similar behaviour is observed for the Risk policy, if we focus on subfigure b we can observe how by increasing the risk threshold and thus reducing the number of transmission, the awareness is increased. Similar behaviours are found for the Risk & Dynamics policy (subfigure c) and the Tracking Trajectories policy (subfigure d). In general, we can observe how the Periodic 5 Hz presents the highest awareness for the low density scenario whereas the Risk & Dynamics policy presents the best performance in the high density scenarios. Although both policies present similar values of awareness for both scenarios. These two policies are situated between the high channel usage of the Periodic 10 Hz and Risk policies and the low channel usage of the Tracking Trajectories and Periodic 1 Hz policies. Thus, these two policies efficiently employ the channel while keeping vehicles updated about their neighbour trajectories.

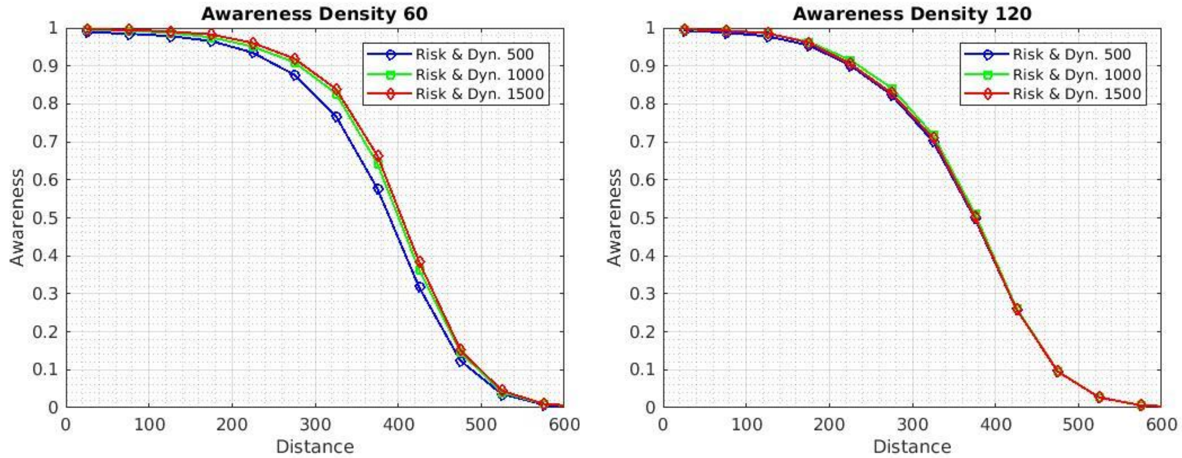
(a)


Awareness Density 60
Awareness Density 120
Periodic 10
Periodic 5
Periodic 1
Risk 500
Track. Traj. 30
Risk & Dyn. 500
Awareness
Distance

(b)


Awareness Density 60
Awareness Density 120
Risk 500
Risk 1000
Risk 1500
Awareness
Distance

(c)


Awareness Density 60
Awareness Density 120
Risk & Dyn. 500
Risk & Dyn. 1000
Risk & Dyn. 1500
Awareness
Distance

(d)

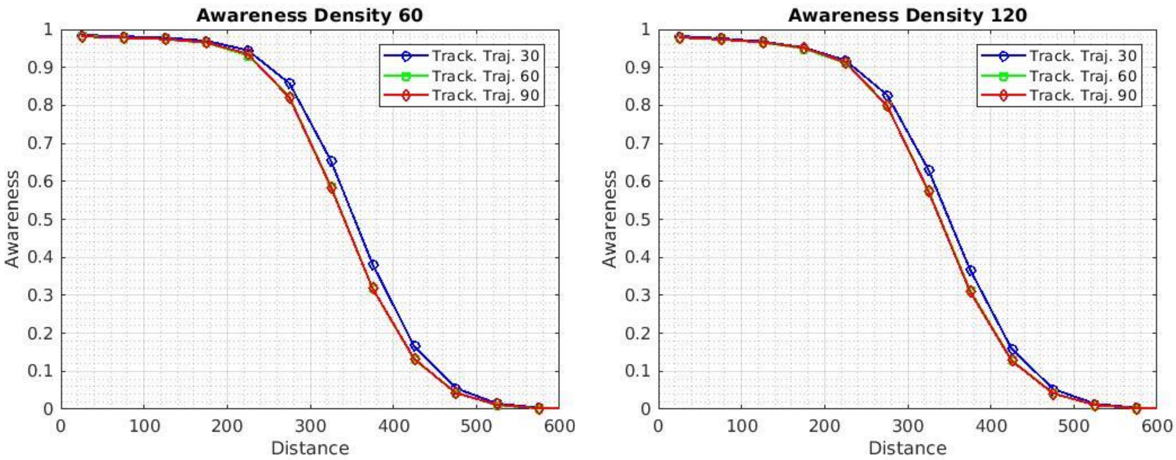
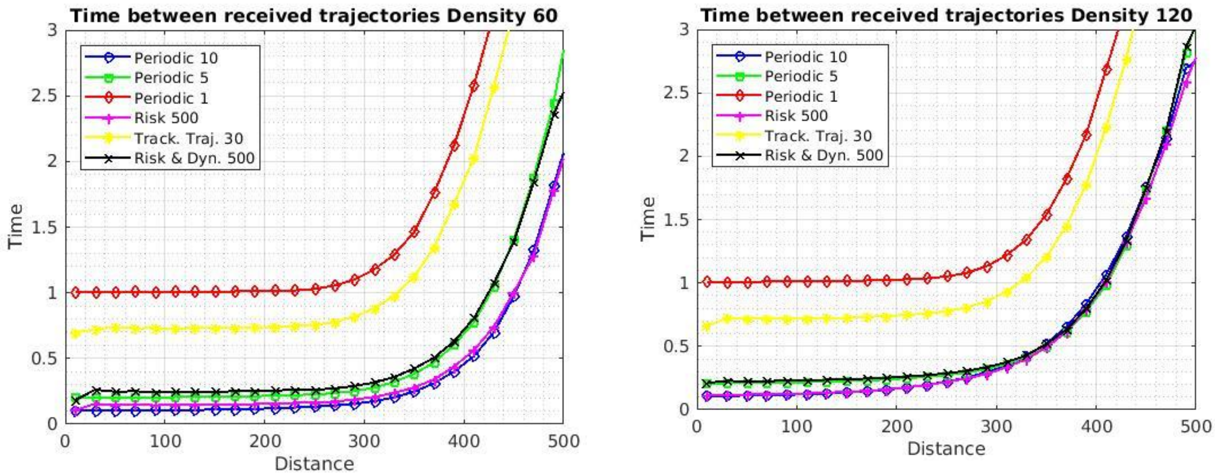


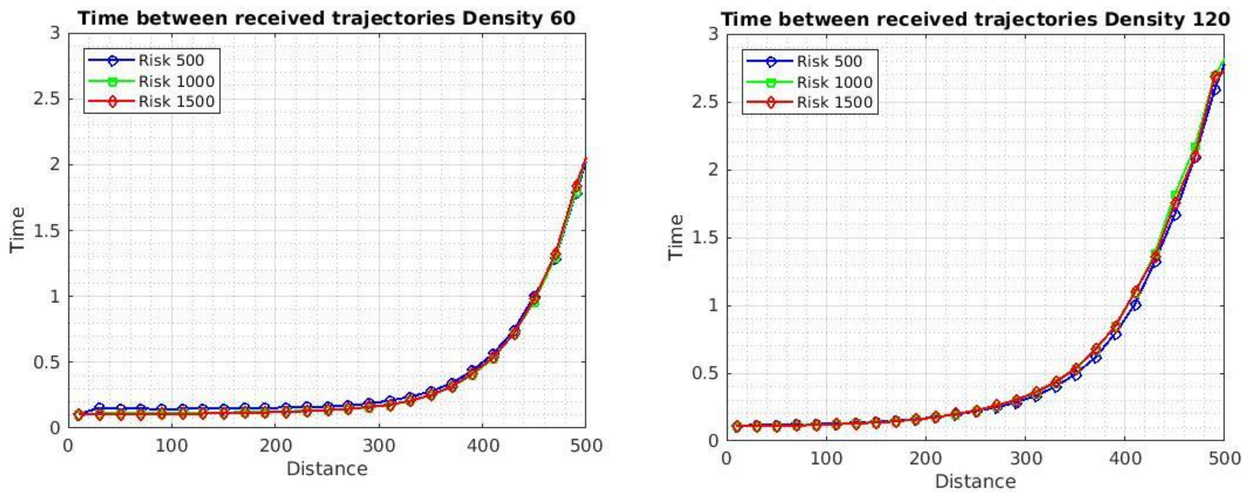
Figure 112 Awareness for the MCM generation rules policies evaluated on two different traffic densities

The awareness metrics gives us insights about the knowledge of the trajectories of neighbour vehicles. However, it is also important to know how often these trajectories are updated. Figure 113 shows the average time between trajectory updates versus the distance between the originating and receiving vehicles. As expected policies that transmit more often present lower average update times, all policies keep an almost constant update time until 300 meters where the update time starts to grow due to packet drops. As in previous metrics, the Risk policy shows a similar behaviour than the Periodic 10Hz policy and the Risk and Dynamic policy shows a similar behaviour than the Periodic 5Hz policy. However, the Tracking Trajectories policy shows a lower update time than the Periodic 1Hz policy which shows us that this policy is able to keep vehicles updated about other vehicles trajectory while using efficiently the communications channel. If we focus on the comparison between the different Tracking Trajectory policies (subfigure d), we observe the reduction of the update time achieved by the 30 cm threshold with respect to the other two threshold employed. This effect can be observed in both traffic densities. Taking into account that the Tracking Trajectories policy only transmits when the trajectory has significantly changed, we can consider that policies with lower average times between received trajectories are transmitting redundant information. This will increase the channel load but some redundancy is needed in order to increase the tolerance of the manoeuvre coordination to packet errors. As seen in Figure 112, the increase of the transmission rate increases the awareness. Therefore, there exists a trade-off between a frequent update of trajectories that increase the redundancy and the awareness and the channel load. The Risk & Dynamics policy is a good candidate for MCM generation rules that take into account this trade-off. However, further research is needed to see if this policy can coexist in the same channel with other messages such as CAM and CPM or it is necessary to employ a policy like the Tracking Trajectories that achieves a more efficient use of the communications channel at the expenses of lower awareness and higher time updates.

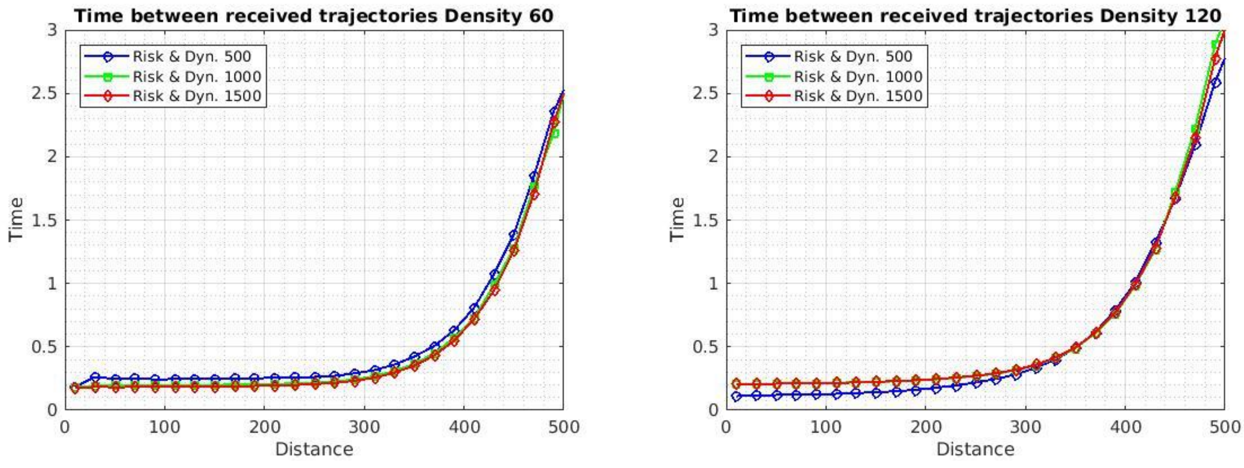
(a
)


Time between received trajectories Density 60
Periodic 10
Periodic 5
Periodic 1
Risk 500
Track. Traj. 30
Risk & Dyn. 500
Time
Distance
Time between received trajectories Density 120
Periodic 10
Periodic 5
Periodic 1
Risk 500
Track. Traj. 30
Risk & Dyn. 500
Time
Distance

(b
)


Time between received trajectories Density 60
Risk 500
Risk 1000
Risk 1500
Time
Distance
Time between received trajectories Density 120
Risk 500
Risk 1000
Risk 1500
Time
Distance

(c
)


Time between received trajectories Density 60
Risk & Dyn. 500
Risk & Dyn. 1000
Risk & Dyn. 1500
Time
Distance
Time between received trajectories Density 120
Risk & Dyn. 500
Risk & Dyn. 1000
Risk & Dyn. 1500
Time
Distance

(d
)

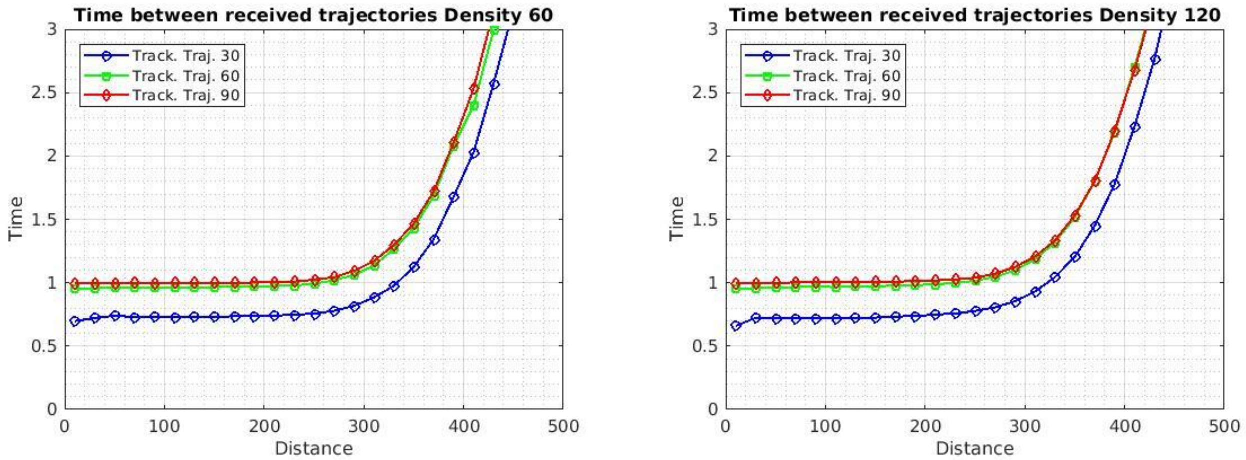


Figure 113 Time elapsed between two consecutive receptions of a message from the same originating station

4 Conclusions

The TransAID project aims at designing traffic management measures for transition areas with mixed traffic scenarios where LV, CV and CAV coexist. Within this context, a key aspect of the TransAID project is to demonstrate how V2X communications can be utilized to allow the cooperation of connected and automated vehicles, leveraging the support of the infrastructure, and to enable their safe coexistence with other conventional and connected vehicles. The cooperation between connected and automated vehicles is addressed in TransAID through the cooperative sensing and cooperative manoeuvres following, and actively contributing, to the ETSI's work items 'DTR/ITS-00183' on collective perception service (CPS) and 'DTS/ITS-00184' on maneuver coordination service (MCS), respectively.

This document has thoroughly analysed the existing works and standardization efforts (especially at ETSI) on cooperative sensing and cooperative driving. As part of the cooperative sensing, this document has also reviewed the available sensors in vehicles and infrastructures and existing techniques to fuse the data these sensors generate. Then, specific sensor fusion techniques that are being developed under TransAID to cope with the challenges that the services defined in TransAID raise. In particular, models to support the merging assistant and techniques to perform the sensor fusion at the vehicle are presented. In addition, this document has presented an in-depth evaluation of the CPM message and the different rules that are being considered at ETSI to generate CPM messages. These rules define which objects should be transmitted in a CPM, and how often they should be transmitted. The conducted analysis has shown the existing trade-off between perception capabilities and communications performance (and network scalability). The conducted analysis has shown that the CPM generation policies that improve the perception capabilities generate higher channel load levels and hence have a higher risk to saturate the communications channel and render the network unstable. While some redundancy could benefit the detection of nearby objects, unnecessary redundancy could severely impact the performance of vehicular networks. The dynamic policy that is currently being considered at ETSI to support the CPM generation achieves an interesting balance between perception capabilities and communications performance. However, it is yet an open discussion whether the observed levels of redundancy are necessary or whether they could be further optimized to reduce any potential negative impact of the implementation of CPM in the stability and scalability of future V2X networks. For this reason, different methods that reduce the level of redundancy included in the CPM have been designed and analysed showing that the reduction of the redundancy can be done while increasing the object perception ratio and reducing the channel load.

Regarding the cooperative driving, this document has introduced the TransAID's proposal to extend the current manoeuvre coordination approach under discussion at ETSI that gives to the road infrastructure the opportunity to support manoeuvre coordination under certain scenarios and conditions. The benefits of the TransAID proposal are discussed, and a detailed analysis of how this proposal can be applied to the Services identified in TransAID is presented. For each of these Services, the message flow required to coordinate the manoeuvres between C(A)Vs is defined. A key message to enable cooperative driving is the MCM that is currently being defined at ETSI. As part of the efforts that TransAID is devoting to contribute to the MCS, this document has also performed an analysis of the generation rules for the MCM. The conducted analysis has highlighted the interest in utilizing dynamic MCM generation rules that take into account the vehicular context. Two different approaches have been presented aiming at adapting the transmission rate based on the existing risk between vehicles and the variations in the trajectory of the transmitting vehicle. The designed approaches will be presented at the ETSI MCS standardization group.

The impact of this deliverable on TransAID can be summarized as follows. The message flow described in this document together with the description of the message format included in

Deliverable 5.1 complete the definition of the V2X message set and communication protocols of the TransAID project. This directly contributes to the achievement of the sub-objective 4 of the project. Similarly, the sensor fusion algorithms included in this document that enhance the detection of conventional vehicles and obstacles on the road contribute to the achievement of the sub-objective 5 of the project. The message flow described in this document will be integrated in WP6 into the iTETRIS platform in order to evaluate on a simulation platform the traffic management procedures defined in WP4 together with the analysis of the performance of the communications protocols defined in WP5. In addition, the V2X message set defined in WP5 will be included in the real world tests developed in WP7.

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Annex A: List of contributions to V2X standardization and specification

1) Universidad Miguel Hernandez de Elche, contribution to the “Intelligent Transport System (ITS); Vehicular Communications; Basic Set of Applications; Analysis of the Collective Perception Service (CPS)”, TR. 103 562.
2) Universidad Miguel Hernandez de Elche, contribution to the “Intelligent Transport Systems (ITS); Vehicular Communication; Informative Report for the Maneuver Coordination Service (MCS)”, TR 103 578.
3) A. Correa et al. (University Miguel Hernandez of Elche), participation at the ETSI ITSWG1-Maneuvering Coordination Service drafting session, 26 February 2018: Introducing TransAID objective and focus for possible MCS service application.
4) A. Correa et al. (University Miguel Hernandez of Elche), participation at the ETSI ITSWG1-Maneuvering Coordination Service drafting session, 18 October 2018: Challenges and solutions for maneuver coordination.
5) A. Correa et al. (University Miguel Hernandez of Elche), participation at the ETSI ITSWG1-Maneuvering Coordination Service drafting session, 21 January 2020: Discussion of TransAID Maneuver Coordination Concept.
6) M. Sepulcre et al. (University Miguel Hernandez of Elche), participation at the ETSI ITSWG1-Collective Perception Service drafting session, 23 January 2019: Simulation Study on Collective Perception.
7) M. Sepulcre et al. (University Miguel Hernandez of Elche), participation at the ETSI ITSWG1-Collective Perception Service drafting session, 12 September 2019: Reduction of CPM Frequency with “Look-Ahead” mechanism.
8) M. Rondinone et al. (Hyundai Motor Europe Technical Center), “Transition Areas for Infrastructure Assisted Driving”, presentation at the C2C-CC Working Group Roadmap meeting, 19 June 2018: Introducing the TransAID services and scenarios for consideration in the C2C-CC roadmapping.
9) A. Correa et al. (University Miguel Hernandez of Elche), “V2X for transition of control in cooperative automated driving”, presentation at the C2C-CC Forum, 21 November 2018.